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A tracer technique to determine sludge deposits in large diameter gas lines

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A TRACER TECHNIQUE TO DETERMINE SLUDGE DEPOSITS IN LARGE DIAMETER GAS LINES

by

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Abstract

A tracer method has been developed to determine the volume of and volumetric flow rate in industrial pipelines and has been applied to determine the sludge build-up in United States Steel Corporation's two 54-inch coke-oven gas pipelines. Sulfur hexafluoride was used as the tracer. For selected sections of pipelines, sludge volumes measured by the tracer technique indicated that sludge occupied 20.5 and 17.7 percent of the volume of two different sections of pipeline. By mechanically probing for sludge at several points along the same sections of the lines, 20.2 and 16.0 percent sludge, respectively, was estimated. In addition to this good agreement obtained by two independent methods, the reliability of the tracer method was further demonstrated by repeating the 20.5 percent sludge measurement in another tracer test on the same section conducted four days later.

The reciprocal Peclet number was also calculated. A comparison with a published empirical correlation showed that the reciprocal Peclet numbers calculated for the gas pipelines were from 1.4 to 13.4 times higher than predicted by the correlation. Bends and curvature of the pipelines, sludge deposits causing nonhomogeneous mixing, nonuniform

flow, and high roughness factors account for the difference between experimental and predicted values. Further, the diameter of the gas lines used in this study was an order of magnitude larger than the diameter of gas lines used in previous studies to measure reciprocal Peclet numbers.

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Because of these problems, it would be useful to know the amount of sludge in the line, in order to determine when to clean the lines or to replace certain sections. A tracer technique has been developed to determine this information. The technique may be especially useful for studies in inaccessible sections of pipe, such as underground sections. In addition to the amount of sludge build-up, the volumetric flow rate, linear velocity, and dispersion number were calculated.

Theory

Longitudinal mixing of fluids flowing in pipes has been studied by numerous investigators(5,6,9,10,11,12). The problem is usually treated using dispersion models, in which the mixing is characterized by an axial dispersion coefficient. The latter can be evaluated using tracer experiments. The tracer is injected at some convenient point in the flow system, and its concentration profile is measured at a point downstream. The tracer may be injected any number of ways, such as a single pulse input, a step input, or a periodic input such as a sine wave. Each type of input produces a different response curve at the downstream measuring point. Danckwerts(2) gives the relationship between these response curves.

For this work, assume the system obeys the axial-dispersed plug-flow model. This model assumes plug flow and negligible concentration gradients in the radial direction. Mixing occurs because of axial dispersion, and the axial dispersion coefficient is assumed constant throughout the system. With these assumptions, the governing differential equation is

$$\frac{\partial C}{\partial \theta} = \frac{D}{uL} \frac{\partial^2 C}{\partial Z^2} - \frac{\partial C}{\partial Z} \qquad (1)$$

where $\frac{D}{uL}$ is the dispersion number, or reciprocal Peclet number, which characterizes the mixing in the system.

Equation (1) may be solved for various systems by using appropriate boundary conditions. The gas pipelines system may be considered to be a doubly-infinite system, that is, extending without limit in both directions from the segment being studied. The boundary conditions are then

$$C = 0 \quad \text{at} \quad z = \pm \infty \tag{2}$$

It is required to find the tracer concentration at z = 1 as a function of time when a pulse of tracer is introduced at the origin (z = 0) when $\theta = 0$. Equation (1) may be solved using the given boundary conditions and initial conditions given by

$$C = 0 \quad \text{for all} \quad z \neq 0 \tag{3}$$

$$\int_{-\infty}^{\infty} C\, A_{free}\, dz = Q \tag{4}$$

With these assumptions the solution is

$$C_\theta = \frac{1}{2\sqrt{\pi\theta\,(D/uL)}} \exp\left[-\frac{(1-\theta)^2}{4\theta\,(D/uL)}\right] \tag{5}$$

Equation (5) describes a set of C_θ versus θ curves with D/uL as a parameter. The dispersion number is related to the variance about the mean dimensionless time of each curve by

$$\frac{D}{uL} = \frac{1}{8}\left(\sqrt{8\sigma_\theta^2 + 1} - 1\right) \tag{6}$$

where

$$\sigma_\theta^2 = \frac{\sigma^2}{\bar{t}^2} \tag{7}$$

Therefore, by measuring the concentration-time profile of an instantaneous pulse of tracer, the dispersion coefficient is calculated by first calculating the variance from the data and then solving Equation (6) for the dispersion number. The dispersion number is then used in Equation (5) to determine C_θ as a function of θ. The derivations of Equations (5) and (6) are given by Levenspiel and Smith(10).

Additional information may be obtained from the concentration-time curve. The stream of tracer leaving the test section may be described by the exit age distribution function, E(t)(3). The fraction of tracer which passes through the pipe in a given time interval is equal to the

area under the E-curve for that time interval. Since all the tracer spends between zero time and infinite time in the test section, the area under the E-curve must equal one; hence

$$\int_0^\infty E(t)\ dt = 1 \tag{8}$$

Danckwerts(3) has shown that E(t) may be determined by a tracer experiment and is given by

$$\frac{Vc(t)}{Q} = E(t) \tag{9}$$

Substituting Equation (9) into Equation (8) and rearranging gives

$$V = \frac{Q}{\int_0^\infty c(t)\ dt} \tag{10}$$

Therefore, the volumetric flow rate is calculated by dividing the quantity of tracer injected by the area under the concentration-time curve.

In addition to the volumetric flow rate, the linear velocity and amount of sludge build-up in the pipe may be determined. As the tracer passes the measuring point,

the concentration rises, goes through a maximum, and falls. The peak of the curve travels at the mean velocity(3). Because the time at which the peak passes the measuring point and the test length are known, the mean velocity is computed by

$$\bar{u} = \frac{L}{\bar{t}} \tag{11}$$

The mean-free cross-sectional area available for flow is the volumetric flow divided by the mean velocity, Equation (10) divided by Equation (11):

$$A_{free} = \frac{V}{\bar{u}} = \frac{Q/\int_0^\infty c(t)\ dt}{L/\bar{t}} \tag{12}$$

Knowing A_{free} and the cross-sectional area of the clean pipe, the fraction of the test section which is filled with sludge is calculated by

$$\% \text{ sludge} = \left(\frac{A_{clean} - A_{free}}{A_{clean}} \right) \times 100 \tag{13}$$

Experimental Procedure and Apparatus

Choice of Tracer and Method of Analysis

Several factors influenced the selection of a suitable tracer for the down-river gas pipelines. They included detection requirements as well as safety considerations. Because of the desire to develop a technique for measuring deposits in gas lines that could be used in any plant, that could be easily transported, and that could be used by plant and research personnel with a minimum of training and supervision, radioactive tracers were not considered. Therefore, the choices were limited to chemical tracers.

The tracer should be non-toxic, non-corrosive, non-flammable, and easy to store(1). Because the sludge calculations require knowing the amount of tracer injected, the tracer must be non-reactive and must not be absorbed by the sludge or the pipe walls. Also, because a rapid injection is required and the volume of gas is large, the tracer should be detectable accurately in the parts per billion (by volume) concentration range.

Sulfur hexafluoride (SF_6) and the halomethanes dichlorodifluoromethane (Freon®-12) and chlorotrifluoromethane (Freon®-13) meet the criteria. All are available commercially in pressurized cylinders and easily handled.

All are detectable at low concentrations by gas chromatographic analysis with an electron capture detector. Sulfur hexafluoride is detectable in lower concentrations than any of the halomethanes. Also, sulfur hexafluoride can be introduced into the pipe more rapidly than the halomethanes because of its lower condensation temperature(5). These last two characteristics make sulfur hexafluoride the more desirable tracer, but the halomethanes would have been acceptable alternatives.

To detect the sulfur hexaflouride in the parts per billion concentration range, a gas chromatograph equipped with an electron capture detector was used. A Perkin-Elmer Sigma 3 gas chromatograph with electron capture detector was available at the Analytical Chemistry and Physics Division of United States Steel Research Laboratory. The detector consists of an electron source and a collection anode. If the chamber containing the source and detector is filled with another electron absorber, such as the fluorine in sulfur hexafluoride, the detector will register a drop in current flow. This drop signals the presence of SF_6 vapor.

Injection and Sampling Procedures

The field injection set-up is illustrated in Figure 1. Pertinent details relating to the equipment are given in Appendix A. Pressure taps are located at various points along the length of the pipelines. These taps are used for probing the lines to test for sludge deposits, among other uses. By connecting a packing gland fitted with a reducer, the taps are convenient for inserting gas-injection probes into the lines. The gas-injection probes are then connected to the exterior equipment.

Commercial purity sulfur hexafluoride is stored in the laboratory in a large pressurized cylinder. The feed tank is filled from the main sulfur hexafluoride cylinder to about 30 psig. In order to minimize contamination of the SF_6, the tank is first evacuated, re-filled with sulfur hexafluoride and evacuated again. The tank is filled with SF_6 again and is now ready for use.

The sulfur hexafluoride feed tank and other equipment is brought to the field and assembled as shown in Figure 1. Holes in the probe provide a planar distribution of tracer and are placed in the direction of the gas flow. Connection of the SF_6 feed tank completes the set-up.

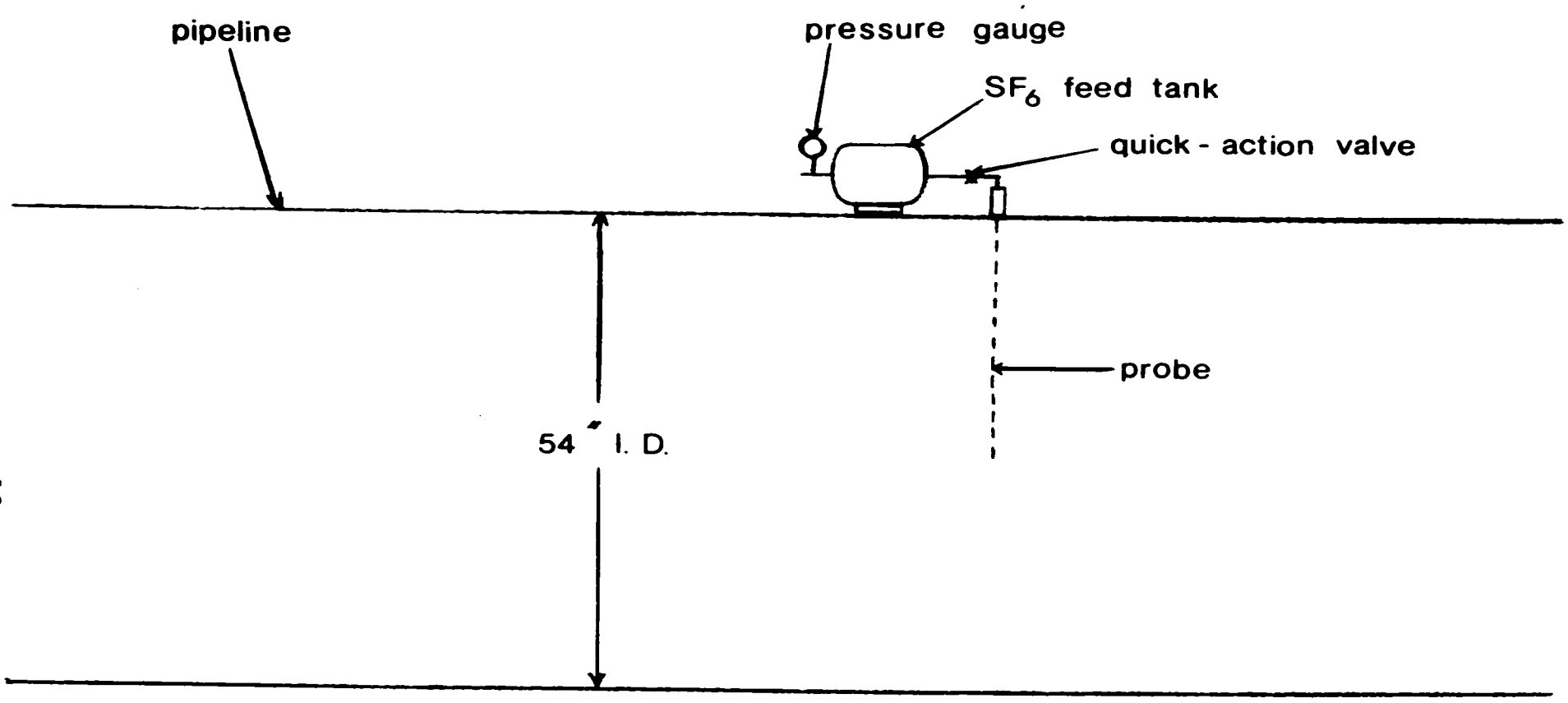


Figure 1 — Injection Set-up

The pressure in the gas lines is usually 8 to 12 psig. Because the SF_6 tank is charged to about 30 psig, the SF_6 can be introduced rapidly into the gas lines by opening and closing the quick-action valve for less than one second. Originally, it was intended to calculate the amount of tracer injected from the feed tank pressure drop, the feed tank volume, and the temperature, and using the ideal gas law in the form

$$V \Delta P = \Delta n RT$$

However, it was discovered that the temperature in the bomb cannot be assumed equal to the ambient temperature and could not be measured accurately and conveniently. This factor suggest using another method to determine the quantity of tracer injected.

The method involved reading the tank pressure drop, as before. Now, however, immediately after injecting the tracer into the gas line, a gas sampling bag was filled with SF_6 using the same-supply tank pressure drop as measured when the tracer was injected into the gas line. The filled bag was then weighed, evacuated, and weighed empty. The amount of tracer was calculated by difference. A check on the consistency of the gas-sampling bag weight method is given in Appendix B.

The sampling set-up is shown in Figure 2. The probe is similar to the injection probe except that the holes now face the gas flow. A knockout pot follows the probe in order to trap any loose sludge. This prevents clogging of the smaller tubing and valves in the sampling manifold. An enclosed bunsen burner is connected to the manifold in order to flare the gas not captured in the sample bags and which flows throughout the sampling period. Check valves are placed between the burner and the manifold to prevent the burner flame from being drawn back into the line. A pinch clamp is used to reduce the gas flow to the burner during sampling. This procedure allows the gas samples to be collected rapidly while at the same time allowing the sampling bags to collect enough gas.

Gas samples were collected in gas sampling bags equipped with an on-off valve and a septum for gas withdrawal by syringe. The valve serves as the connection to the manifold when being used in the field. Samples may remain in the bags for several weeks without affecting the composition, and the bags may be reused many times. After analysis, the bags are evacuated by connecting to a vacuum pump, filling with air, and evacuating again. This procedure minimizes contamination of the next sample.

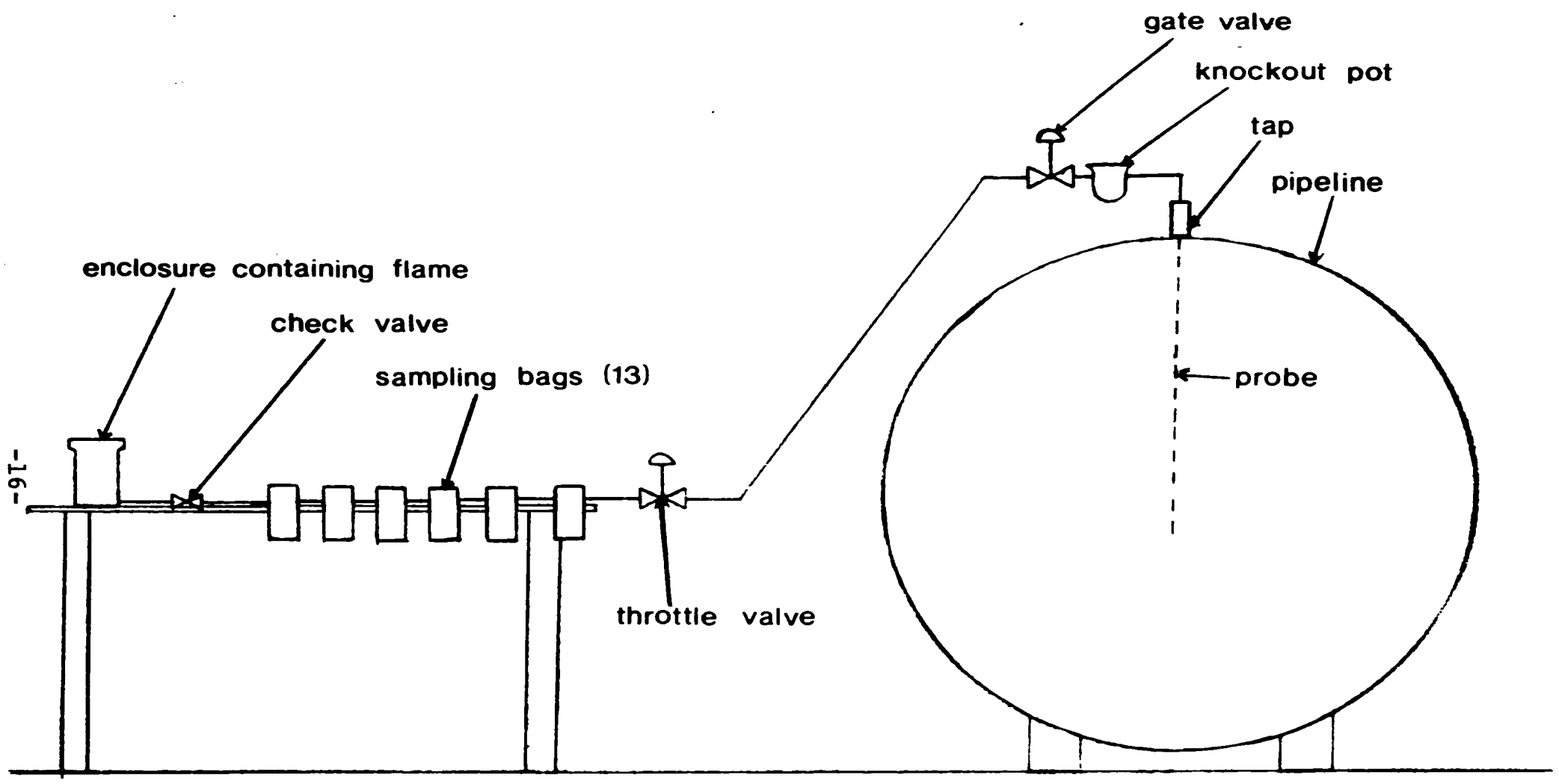


Figure 2 — Sampling Set-up

The chosen system provides for a limited number of samples, and it is critical to determine the proper time for sampling. The time depends on the linear velocity. However, the linear velocity cannot be estimated from the volumetric flow rate because the volumetric flow rate is not accurately known at the instant of sampling. Also, the area available for flow is not known before the experiment. Since the samples cannot be analyzed in the field, an "on-the-spot-technique" was developed to indicate the beginning of the sampling process.

The method used involves the use of the copper flame test for halogens, known as the Beilstein test. The gas passes through a Bunsen burner flame in which a copper rod in suspended. The halogen present in the gas reacts with the copper to impart a green color to the flame. A problem which was encountered initially was that the copper would occasionally burn green without the presence of halogen. No satisfactory explanation was found for this reaction. It was found, however, that after allowing the copper to remain in the flame for ten to fifteen minutes, the green would disappear, and the copper could then be used.

Even though the Beilstein test is a halogen test, it was observed that fluorine did not impart the green flame. Therefore, sulfur hexafluoride could not be used for the flame test. Chlorine gives a distinct green flame. Freon®-12 is excellent for the test. A feed tank similar to the SF_6 tank is filled with Freon®-12 to about 100 psig. A 40 to 50 psig pressure drop over ten to fifteen seconds is a sufficient injection to impart the green flame at the sampling point. This injection precedes the sulfur hexafluoride injection. Because the Freon®-12 is only an indicator, the injection need not be a pulse injection, and indeed should not be because enough Freon® will not be injected in a pulse to induce a green-colored flame at the sampling point. Also, because bright sunshine makes it difficult to see the flame, the burner set-up is placed in a closed black can with a window.

Samples are taken in equally spaced time intervals. The length of the time interval depends on the test length. A table of recommended time intervals for ranges of test lengths is given in Appendix C.

The gas samples are brought to the Research Laboratory for analysis. Data reports are summarized in Appendix D. In order to account for the line pressure, the reported

concentrations must be corrected by multiplying by the ratio of line pressure to atmospheric pressure. The results of this correction are summarized in the first three columns of Table I.

Discussion of Results

Graphs 1 through 9 are the plots of actual concentration versus time. The concentration-time curve provides the basis for the sludge calculations. Appendix E gives a sample calculation for the percent sludge. The concentration-time curve is needed in order to obtain the area under the curve and the peak time. A summary of the pertinent results from the calculations is given in Table II. For runs from 8/9 and 8/16, the percent sludge could not be calculated because the quantity of tracer injected was not accurately determined. The quantity injected as determined from the ideal gas law was found to be about 50 percent higher than the amount determined from the method of weighing a sample bag filled with gas. When using the quantity as determined from the ideal gas law, the calculation resulted in negative values for the percent sludge. Beginning with the runs of 8/18, the amount of SF_6 injected was determined by the gas sampling bag weight method. All runs after 8/18/78 except 11/10/78 gave reliable results. On checking records at Carnegie Natural Gas Company's mixing station, it was discovered that at the time of the 11/10/78 test there was a significant pressure fluctutation in the line. This may have been

the result of a variable gas flow or some other disturbance in the system. Because the 11/10/78 run is the only unsuccessful run after the gas sampling bag weight method was initiated, and because the procedure has not been altered since 8/18/78, the pressure fluctuation may be an explanation for the unsuccessful run.

Runs 8/18 and 8/22 (1) and (2) were made on the same test section. The discrepancy in percent sludge for run 8/22 (1) is accounted for by the fact that the sample bag that contained an amount of SF_6 equal to the amount injected into the pipeline leaked, and hence the amount of SF_6 injected could only be approximated from the feed tank pressure drop. The 20.5 percent sludge is considered accurate because the same result was obtained for two independent runs. Also, 20.5 percent corresponds to a 14-inch sludge depth evenly distributed over the test length of the 54-inch diameter pipe, and the average depth of sludge obtained by mechanically probing the same section of pipeline was 13.8 inches as measured on 4/18/78. Similarly, the 8/24 result (13 inches) agreed agreed well with the dip results (11.7 inches). Dip checks were not obtained for 2/6 data, and 2/9 data was taken on an underground section; hence, a dip check was not possible.

The volumetric flow rate and velocity may also be calculated. Because the volumetric flow is calculated from the quantity of tracer injected, the values could not be determined for runs 8/9, 8/16, and 11/10. The velocity may be calculated from the peak time and the known test section length. The peak time of the curve is unaffected by the magnitude of the concentration values; hence, the velocity may always be calculated, assuming the peak of the curve is obtained. The velocities in Table II are considered reliable because they also have been confirmed by calculations using the green flame signal from the Freon® injection.

In addition to determination of percent sludge, other calculations may be performed. From the variance of the concentration time curve and the peak time, the dispersion number may be calculated, as shown in Part II, Appendix E. The values of the dispersion number obtained for all runs are summarized in Table III along with the predicted values from Levenspiel(9). Because these values depend only on the concentration-time curve and pulse injection and not on the quantity of tracer injected, the dispersion numbers may be calculated for any runs where the concentration-time curve has been obtained. Thus, D/uL values are reported for

every run. Using the dispersion numbers obtained from the variances of the experimental concentration-time curves and Equation (5), the dimensionless concentrations may be calculated for values of the dimensionless time. These values, along with experimental C_θ values, values calculated using the predicted dispersion number, and dimensionless times, are given in the last four columns of Table I. Graphs 10 through 18 show the relationship between the dimensionless concentration values.

The graphs show good agreement between experimental C_θ values and C_θ values calculated using the experimentally determined dispersion number in Equation (5). This result demonstrates that the doubly infinite axial-dispersed plug flow model is an appropriate model for the system. The C_θ curves calculated using the predicted dispersion number are narrower and have a higher peak C_θ value than the experimental curves. The C_θ versus θ curves are a function of the dispersion number. As D/uL decreases, the curve becomes narrower with a higher peak(8). Equation (7) also shows this result. As D/uL decreases, the variance becomes smaller; hence, the curve becomes narrower.

Experimental and predicted dispersion numbers are listed in Table III. The predicted values were determined

from a graph given by Levenspiel(9). The graph plots the ratio $\frac{D}{ud_t}$ as a function of Reynolds number. For the coke-oven gas lines, the Reynolds number is high, and, therefore, the predicted D/ud_t always falls in the asymptotic region of the curve. Multiplying by the geometric factor d_t/L gives the dispersion number. All runs except 8/16 give experimental dispersion numbers significantly greater than those predicted. These higher values of D/uL indicate greater mixing than expected in the system. This is further illustrated by graphs 10 through 18, which show a wider spread of tracer than predicted. Taylor(12) states that small amounts of curvature greatly increase the degree of dispersion. Because the experiment was performed on an industrial line which follows the terrain on which it was built, there are significant curves and bends in the pipeline. In addition to curvature of the pipeline, the sludge deposits in the line may cause some increase in mixing. The uneven distribution of the sludge might cause eddy formation and backmixing. Also, it was observed that the flow pulses, which would increase mixing. This enhanced mixing results in nonhomogeneous fluid mixing. If the mixing is not homogeneous, the dispersion coefficient, D, which results from the calculation

is an average value, which would not be expected to correlate with the expected value unless the flow patterns could be accounted for(9).

The roughness of the pipeline may also partly account for the higher experimental dispersion number. Levenspiel's plot of D/ud_t versus Reynolds number is for commercial pipe and is correlated by

$$\frac{D}{ud_t} = 3.57\sqrt{f} \tag{14}$$

where f is the Fanning friction factor(9). Because f is a function of Reynolds number and relative roughness, a family of curves for different roughness values are obtained(9). Although the gas lines may be considered commercial pipe, years of service have caused pitting and corrosion of many sections of the line. This pitting increases the roughness. From the familiar friction factor-Reynolds number charts, as ε/d_t increases, f increases (for constant Re). From Equation (14), as f increases, D/ud_t increases. Hence, the greater pipe roughness results in higher predicted dispersion numbers which differ less from the experimentally determined values.

Occasionally, when taking data in the field, the entire concentration time curve may not be detected. Rather than extrapolate hand-drawn curves, it would be desirable to predict the parameters D/uL, peak time, and area under the concentration-time curve analytically, and then use these values to perform the sludge calculations. A computer program has been written to perform these calculations. The key part of the program uses a modified Levenberg-Marquardt algorithm which finds the minimum of the sum of the squares of M functions in N variables(13). Run 8/18/78 calculations were made using the computer program. The program is considered reliable because the result of 20.5 percent sludge calculated by the program was obtained for another run made on the same section of pipeline four days later.

Table I—Data Summary

Date 8/9/78 Predicted $\frac{D}{uL}$ = 0.00130 Calculated $\frac{D}{uL}$ = 0.00404

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
20	-	-				
22	-	-	0.747	0.000	0.026	0.000
24	529	897	0.815	0.029	0.366	0.003
26	31,027	52,779	0.883	1.729	1.810	0.422
28	88,051	149,784	0.951	4.908	3.893	4.935
30	88,884	151,210	1.019	4.955	4.301	7.237
32	23,066	39,244	1.087	1.286	2.767	1.966
34	9755	16,595	1.154	0.544	1.158	0.140
36	4133	7032	1.222	0.230	0.331	0.003
38	1986	3380	1.290	0.111	0.069	0.000
40	1602	2723	1.358	0.089	0.011	0.000
42	1329	2259	1.426	0.074	0.001	0.000
44	625	1057	1.494	0.035	0.000	0.000
			1.562	0.000	0.000	0.000

(Continued)

Table I—Data Summary (Continued)

Date 8/16/78 Predicted $\frac{D}{uL}$ = 0.00041 Calculated $\frac{D}{uL}$ = 0.00059

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
80	-	-				
82	-	-				
84	-	-	0.884	0.000	0.020	0.001
86	2146	3652	0.906	0.328	0.196	0.038
88	8570	14,592	0.927	1.311	1.055	0.435
90	28,496	48,535	0.948	4.360	3.561	2.513
92	51,258	87,314	0.969	7.844	7.748	7.730
94	68,974	117,492	0.990	10.555	11.180	13.164
96	78,568	133,830	1.011	12.022	10.976	12.879
98	53,660	91,399	1.032	8.211	7.506	7.488
100	28,256	48,134	1.053	4.324	3.654	2.669
102	5750	9787	1.074	0.879	1.291	0.600
104	1618	2755	1.095	0.278	0.338	0.087
			1.116	0.000	0.066	0.008

(Continued)

Table I—Data Summary (Continued)

Date 8/18/78 Predicted $\frac{D}{uL}$ = 0.00041 Calculated $\frac{D}{uL}$ = 0.00180

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
30	24,556	38,395	0.906	1.871	2.047	0.038
33	87,650	137,034	0.997	6.679	6.651	13.876
36	29,713	46,452	1.088	2.264	2.372	0.174
39	6920	10,812	1.178	0.527	0.146	0.000
42	1890	2947	1.269	0.144	0.002	0.000

(Continued)

Table I—Data Summary (Continued)

Date 8/22/78 (1) Predicted $\frac{D}{uL}$ = 0.00041 Calculated $\frac{D}{uL}$ = 0.00348

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
30	-	-				
35	-	-	0.695	0.000	0.001	0.000
40	465	721	0.795	0.031	0.165	0.000
45	30,306	47,493	0.894	2.021	2.129	0.007
50	81,564	127,808	0.993	5.439	4.553	13.565
55	21,144	33,125	1.093	1.410	2.605	0.107
60	6007	9419	1.192	0.401	0.560	0.000
65	1938	3043	1.291	0.130	0.057	0.000
70	465	721	1.391	0.031	0.003	0.000
			1.490	0.000	0.000	0.000

(Continued)

Table I—Data Summary (Continued)

Date 8/22/78 (2) Predicted $\frac{D}{uL}$ = 0.00041 Calculated $\frac{D}{uL}$ = 0.00134

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
40	-	-	0.782	0.000	0.000	0.000
43	625	977	0.841	0.072	0.031	0.000
46	5446	8554	0.900	0.631	1.022	0.017
49	59,154	92,872	0.958	6.846	5.584	4.631
52	57,152	89,733	1.017	6.615	7.247	11.616
55	18,549	29,121	1.076	2.147	2.729	0.509
58	5510	8650	1.134	0.638	0.354	0.001
61	-	-	1.193	0.000	0.021	0.000

(Continued)

Table I—Data Summary (Continued)

Date 8/24/78 Predicted $\frac{D}{uL}$ = 0.00041 Calculated $\frac{D}{uL}$ = 0.00191

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
50	-	-				
53	-	-				
56	-	-	0.819	0.000	0.038	0.000
59	1794	2803	0.863	0.115	0.403	0.000
62	28,528	44,594	0.907	1.830	1.945	0.044
65	103,717	162,150	0.951	6.654	4.754	3.064
68	95,740	149,672	0.995	6.142	6.450	13.753
71	76,983	120,359	1.039	4.939	5.228	5.597
74	31,716	49,576	1.083	2.034	2.698	0.277
77	10,075	15,746	1.126	0.646	0.961	0.002
80	3988	6231	1.170	0.256	0.235	0.000
83	2098	3284	1.214	0.135	0.042	0.000
86	2002	3124	1.258	0.128	0.006	0.000
			1.302	0.000	0.001	0.000

(Continued)

Table I—Data Summary (Continued)

Date 11/10/78 Predicted $\frac{D}{uL}$ = 0.00082 Calculated $\frac{D}{uL}$ = 0.00134

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
90	-	-				
95	-	-				
100	-	-	0.894	0.000	0.781	0.226
105	7849	13,535	0.939	1.391	3.797	3.037
110	53,933	93,001	0.984	9.560	7.400	9.174
115	45,988	79,305	1.029	8.152	6.522	7.569
120	12,542	21,624	1.073	2.223	2.945	2.092
125	2659	4581	1.118	0.471	0.714	0.209
130	1041	1794	1.163	0.184	0.093	0.009
135	913	1570	1.208	0.161	0.009	0.000
140	609	1057	1.252	0.109	0.001	0.000
145	529	913	1.297	0.094	0.000	0.000
150	481	833	1.342	0.086	0.000	0.000
			1.386	0.000	0.000	0.000

(Continued)

Table I—Data Summary (Continued)

Date 2/6/79 Predicted $\frac{D}{uL}$ = 0.00017 Calculated $\frac{D}{uL}$ = 0.00072

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
230	0	0	0.892	0.000	0.130	0.000
240	3668	6119	0.931	0.724	1.845	0.012
250	44,562	74,275	0.970	8.786	7.734	5.613
260	62,438	104,069	1.009	12.311	10.178	19.141
270	15,105	25,180	1.048	2.979	4.787	0.833
280	3172	5286	1.087	0.625	0.899	0.001
290	1121	1874	1.125	0.222	0.080	0.000
300	432	721	1.164	0.085	0.003	0.000
310	529	881	1.203	0.104	0.000	0.000
320	432	721	1.242	0.085	0.000	0.000

(Continued)

Table I—Data Summary (Continued)

Date 2/9/79 Predicted $\frac{D}{uL}$ = 0.000088 Calculated $\frac{D}{uL}$ = 0.00118

Time, sec	Std Conc, $kg/m^3 \times 10^9$	Conv Conc, $kg/m^3 \times 10^9$	$\theta = \frac{t}{\bar{t}}$	C_θ (experimental)	C_θ (calculated)	C_θ (predicted)
220	-	-				
230	-	-				
240	-	-	0.888	0.022	0.437	0.000
250	609	849	0.925	0.060	2.354	0.000
260	44,258	61,573	0.962	4.384	6.092	0.431
270	138,059	192,056	0.999	13.675	8.214	30.001
280	54,653	76,037	1.036	5.414	6.190	0.845
290	16,162	24,492	1.073	1.744	2.672	0.000
300	7512	10,444	1.110	0.744	0.774	0.000
310	4725	6567	1.147	0.468	0.142	0.000
320	3444	4789	1.184	0.341	0.018	0.000
330	1842	2563	1.221	0.182	0.002	0.000
340	1666	2323	1.258	0.165	0.000	0.000

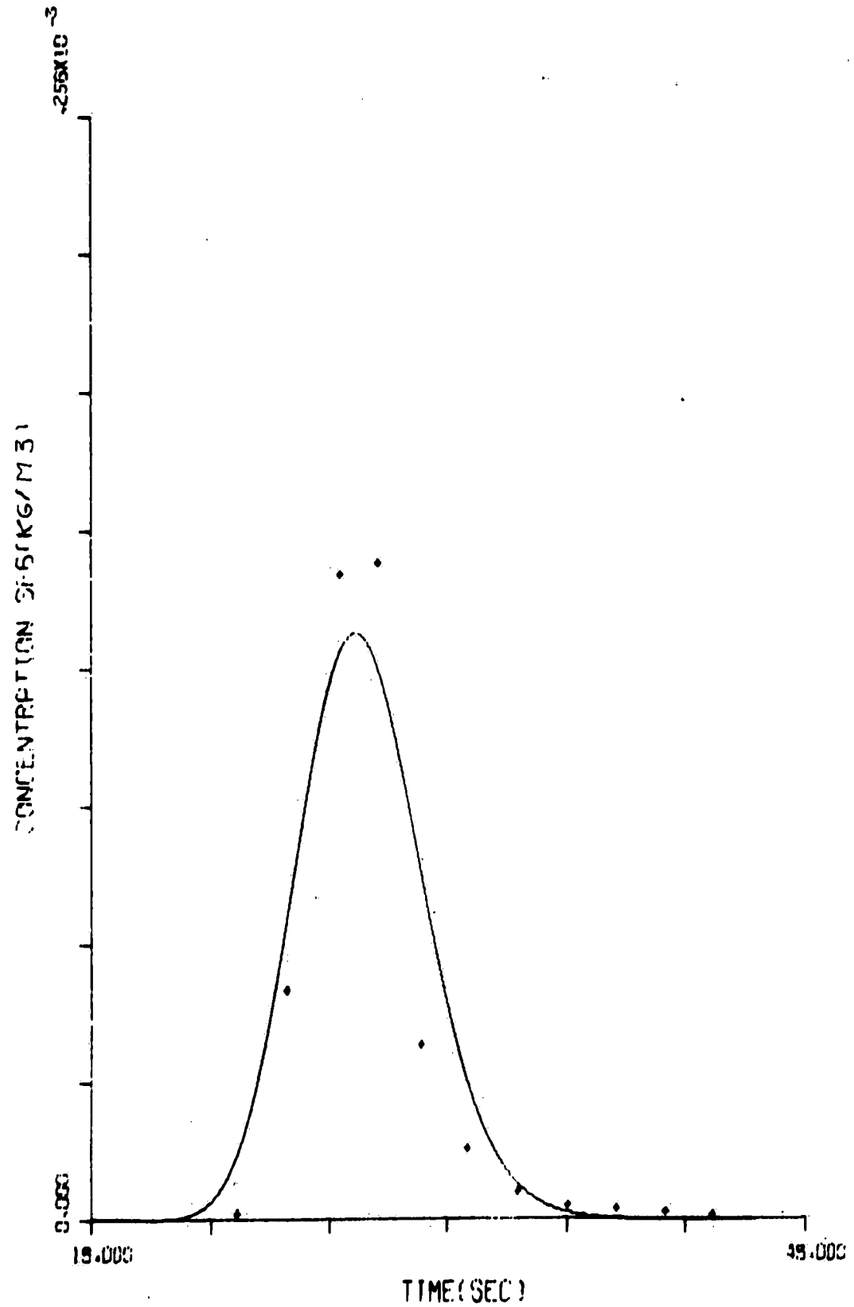
Table II—Summary of Percent Sludge Calculations

Date	Area under c,t-Curve, kg sec/m^3	Peak Time, sec	Test Length, m	Quantity Tracer Injected, kg	Volumetric Flow, m^3/sec	Velocity, m/sec	% Sludge
8/9/78	8.99×10^{-4}	29.2	222	-	-	7.6	-
8/16	1.03×10^{-3}	96.0	710	-	-	7.4	-
8/18	6.79×10^{-4}	33.1	704	0.0170	25.0	21.3	20.5
8/22 (1)	1.18×10^{-3}	49.7	704	0.0114*	9.6	14.2	54.0
8/22 (2)	6.94×10^{-4}	50.4	704	0.0114	16.4	14.0	20.5
8/24	1.67×10^{-3}	66.2	710	0.0218	13.0	10.7	17.7
11/10	1.09×10^{-3}	111.8	351	0.0137	12.5	3.1	(-171)
2/6/79	2.18×10^{-3}	257.7	1731	0.0120	5.5	6.7	44.5
2/9**	3.80×10^{-3}	270.3	2181	0.0122	3.2	8.1	39.6

* assumed; bag containing SF_6 was lost

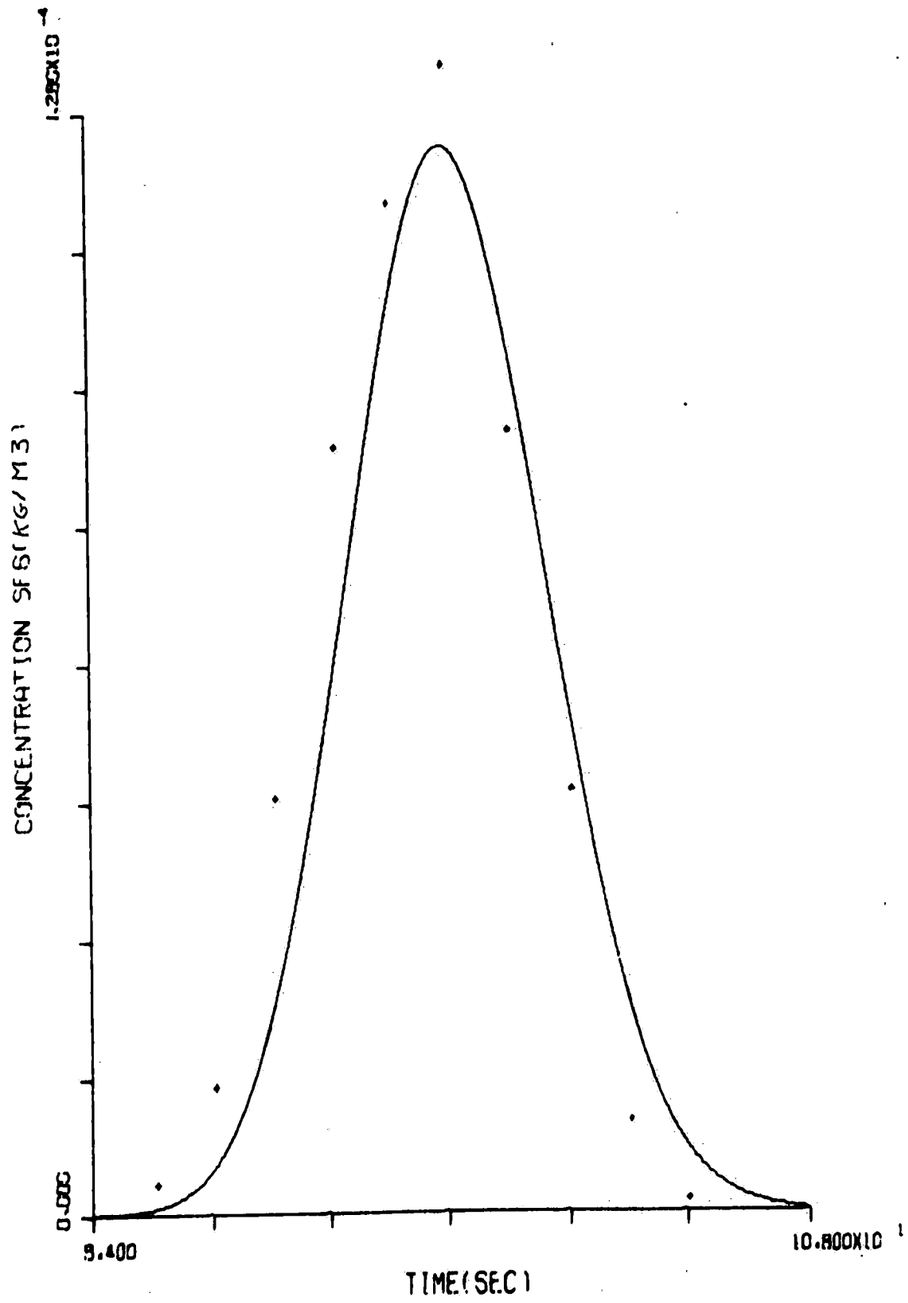
** run on 36-inch diameter line

Graph No. 1



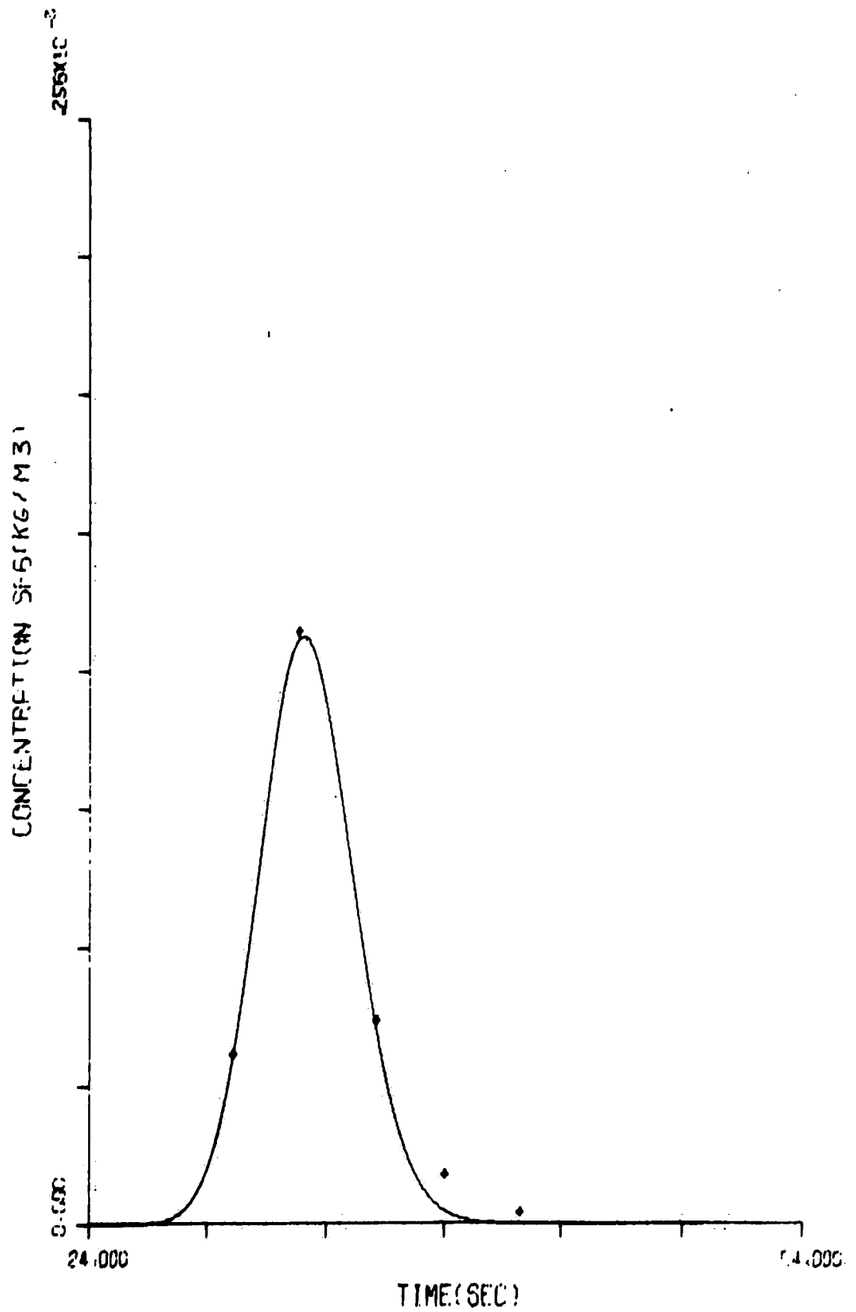
CONCENTRATION TIME CURVE (8/9/78)

Graph No. 2



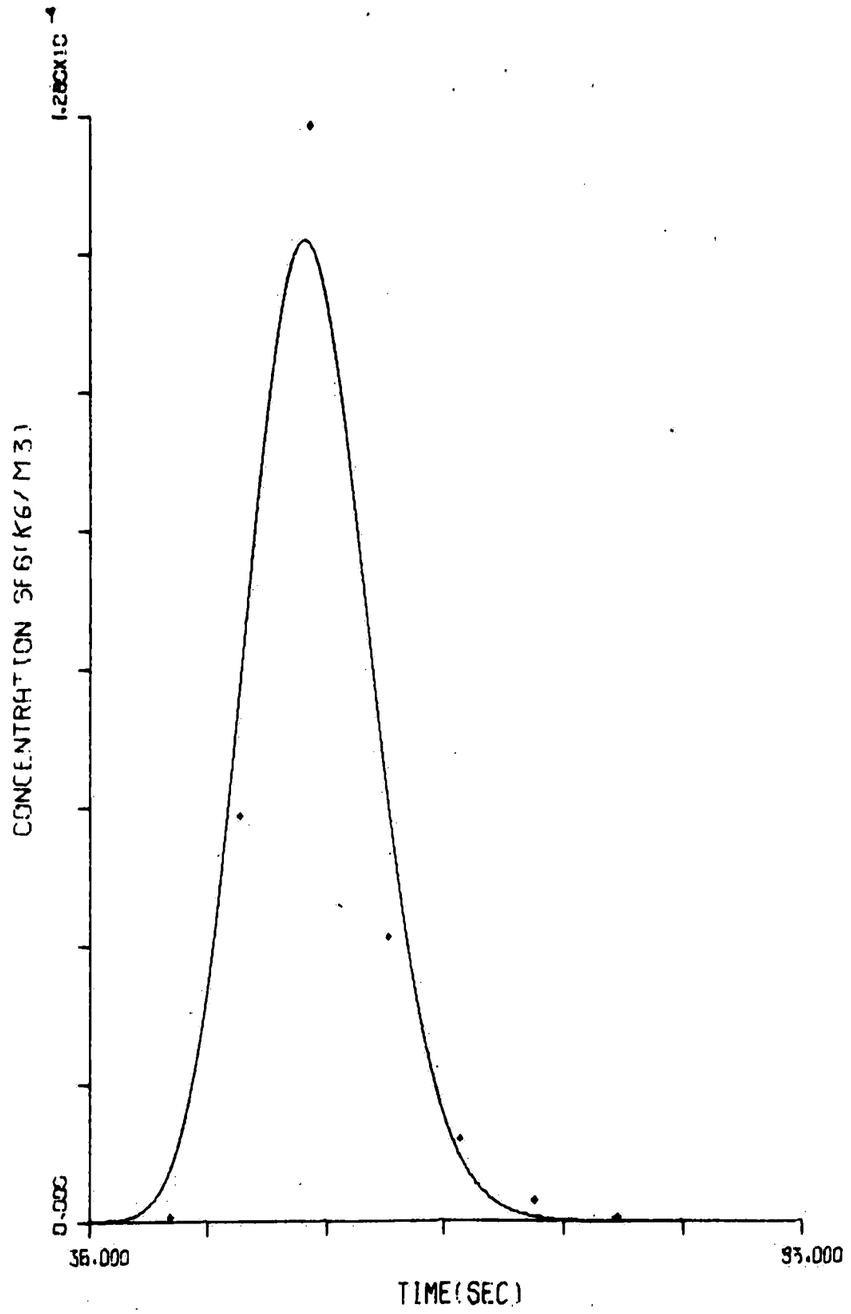
CONCENTRATION-TIME CURVE (8/16/78)

Graph No. 3



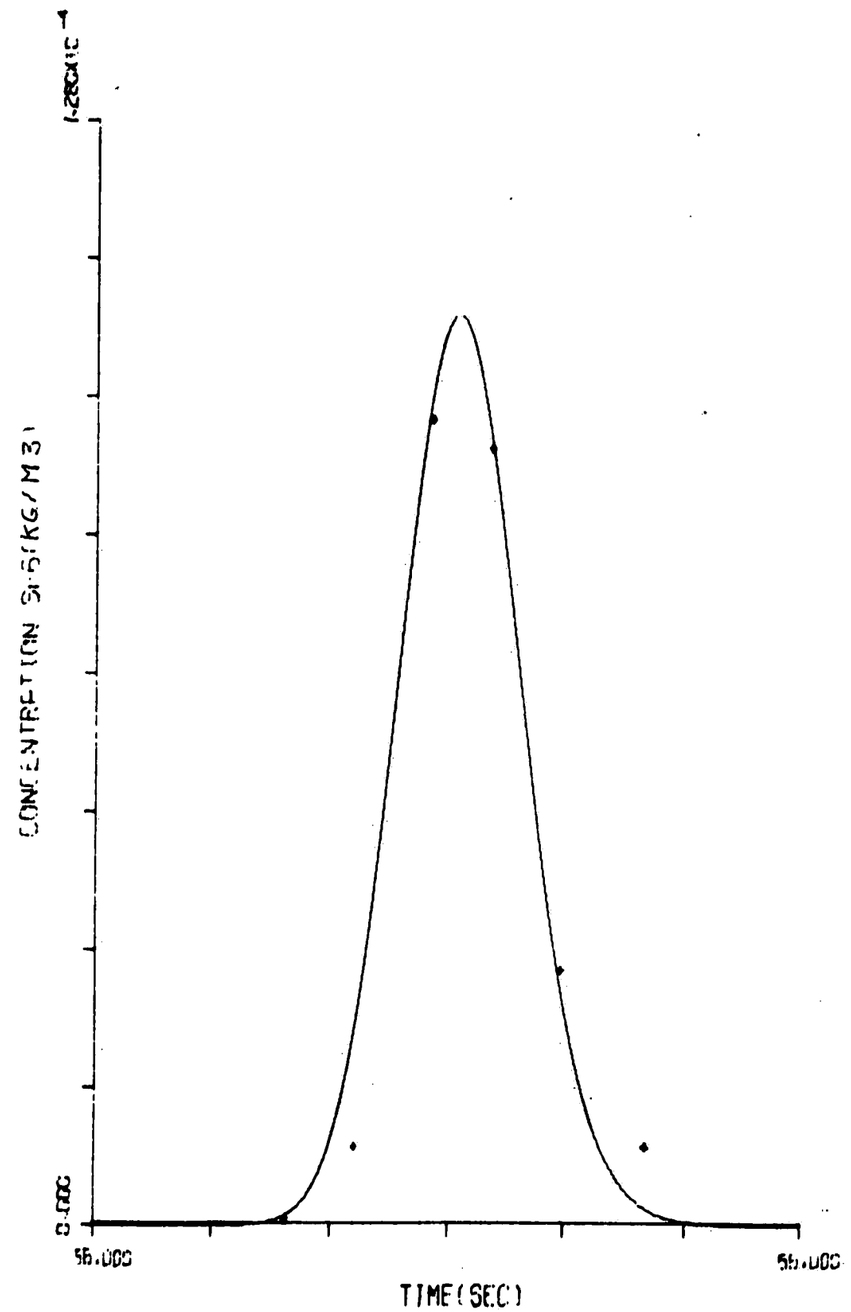
CONCENTRATION-TIME CURVE (8/18/78)

Graph No. 4



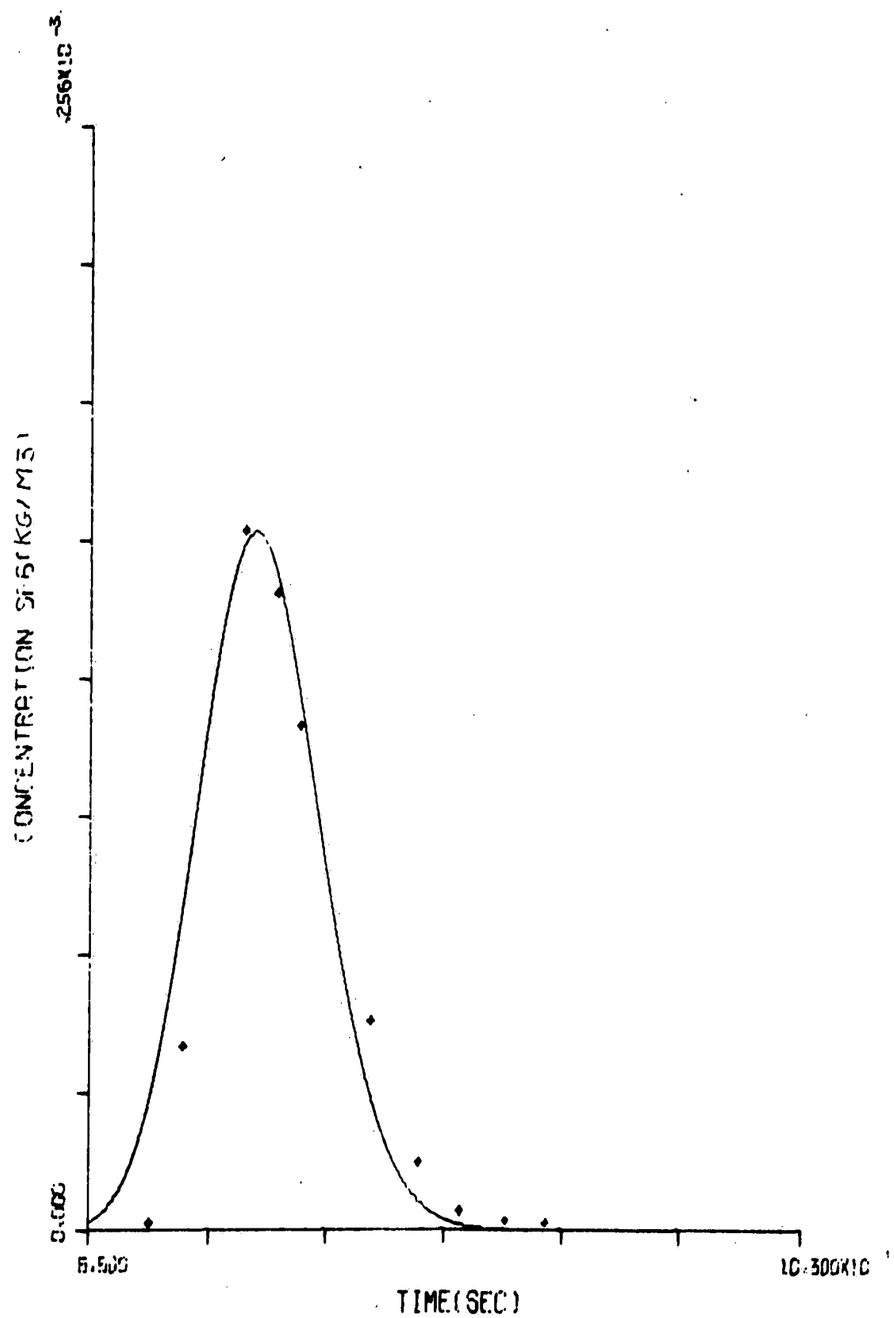
CONCENTRATION-TIME CURVE (8/22/78)

Graph No. 5



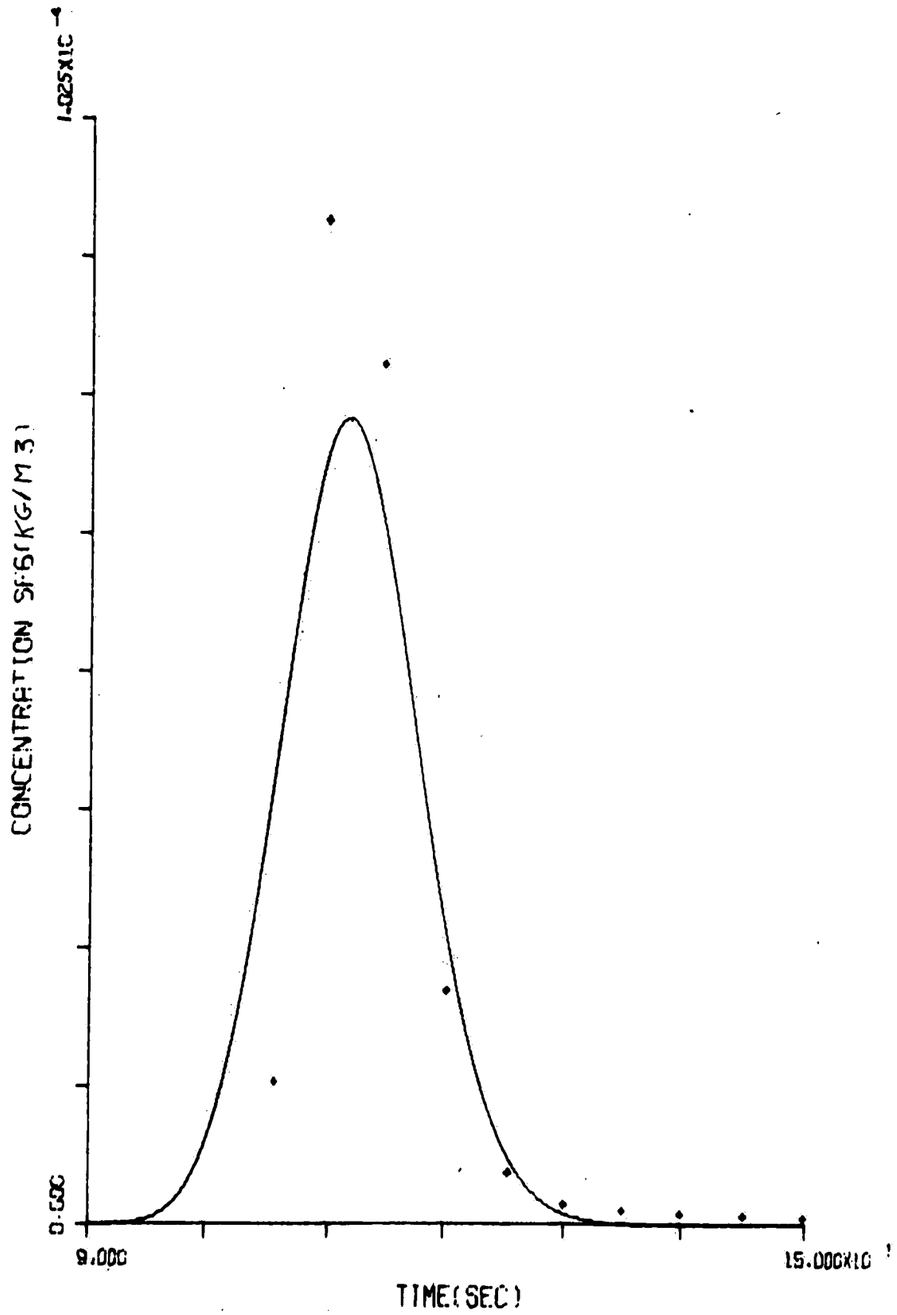
CONCENTRATION-TIME CURVE (8/22/78)

Graph No. 6



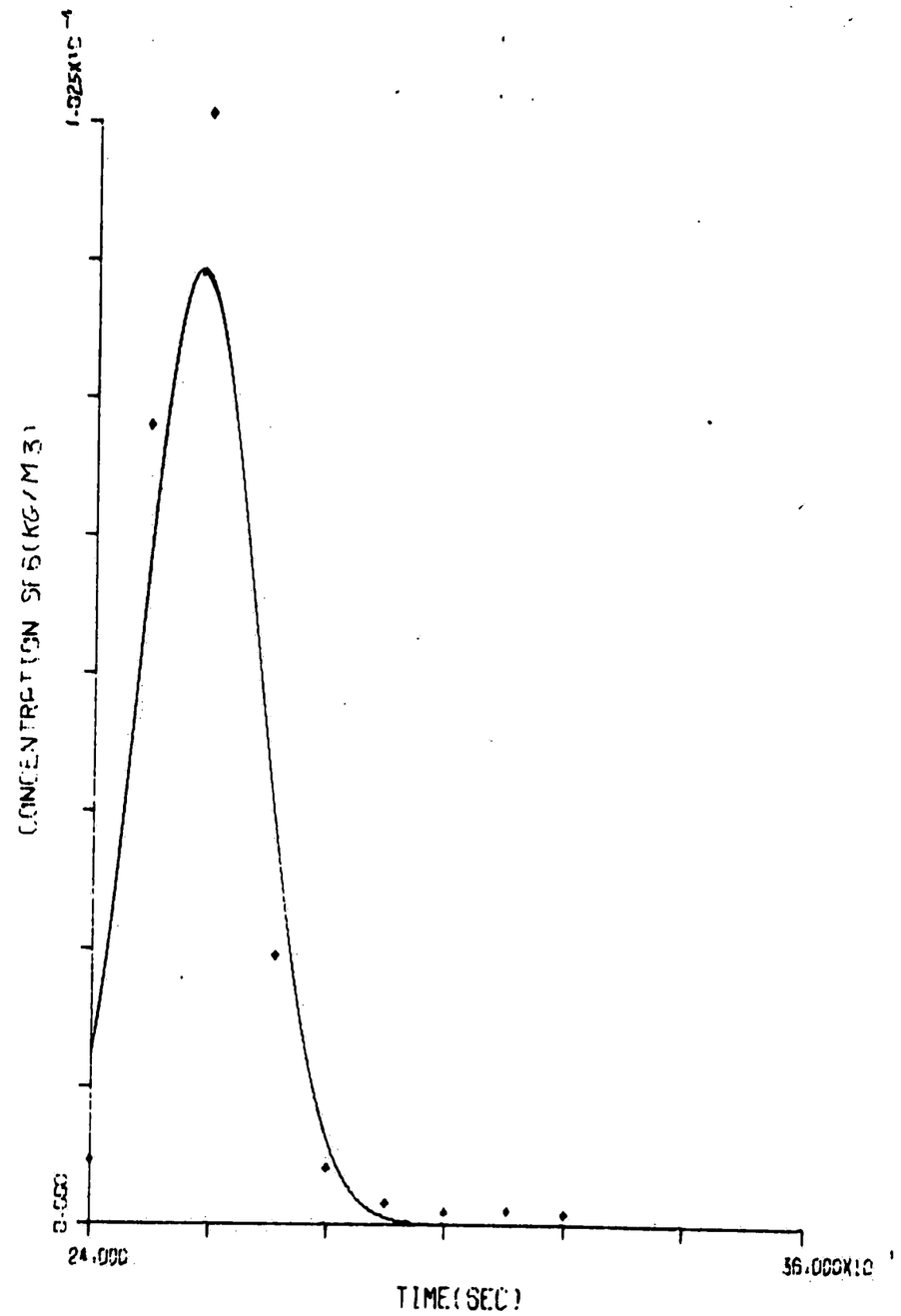
CONCENTRATION-TIME CURVE (8/24/78)

Graph No. 7



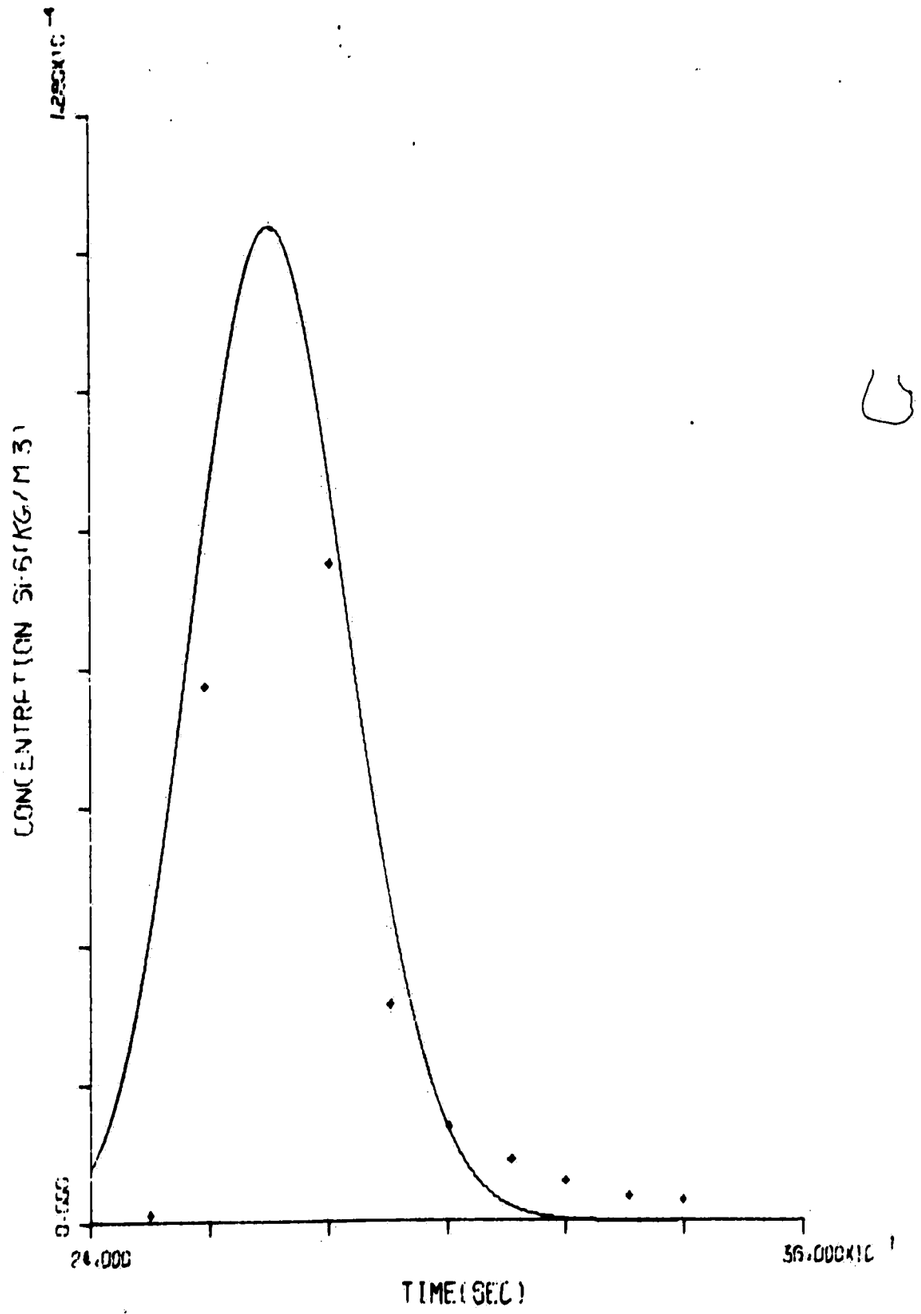
CONCENTRATION-TIME CURVE (11/10/78)

Graph No. 8



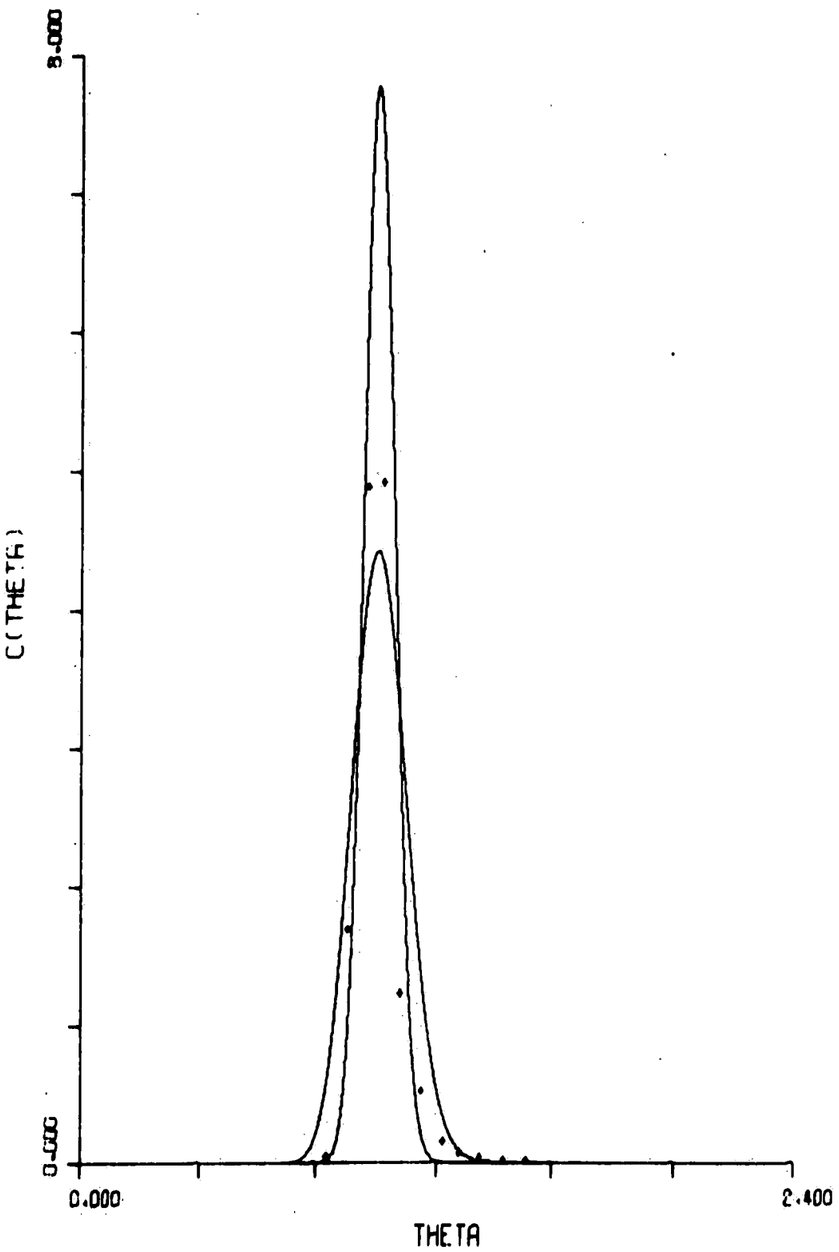
CONCENTRATION-TIME CURVE (2/6/79)

Graph No. 9



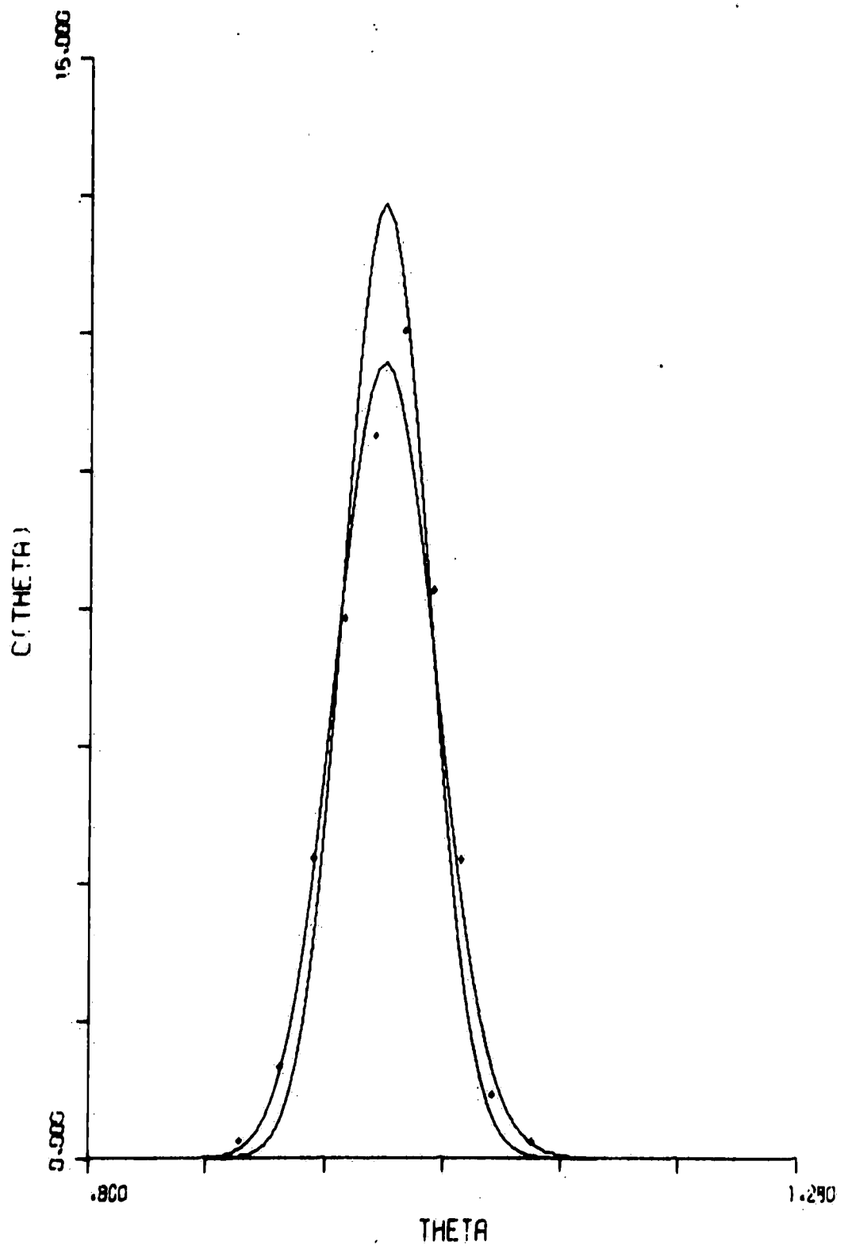
CONCENTRATION-TIME CURVE (2/9/79)

Graph No. 10



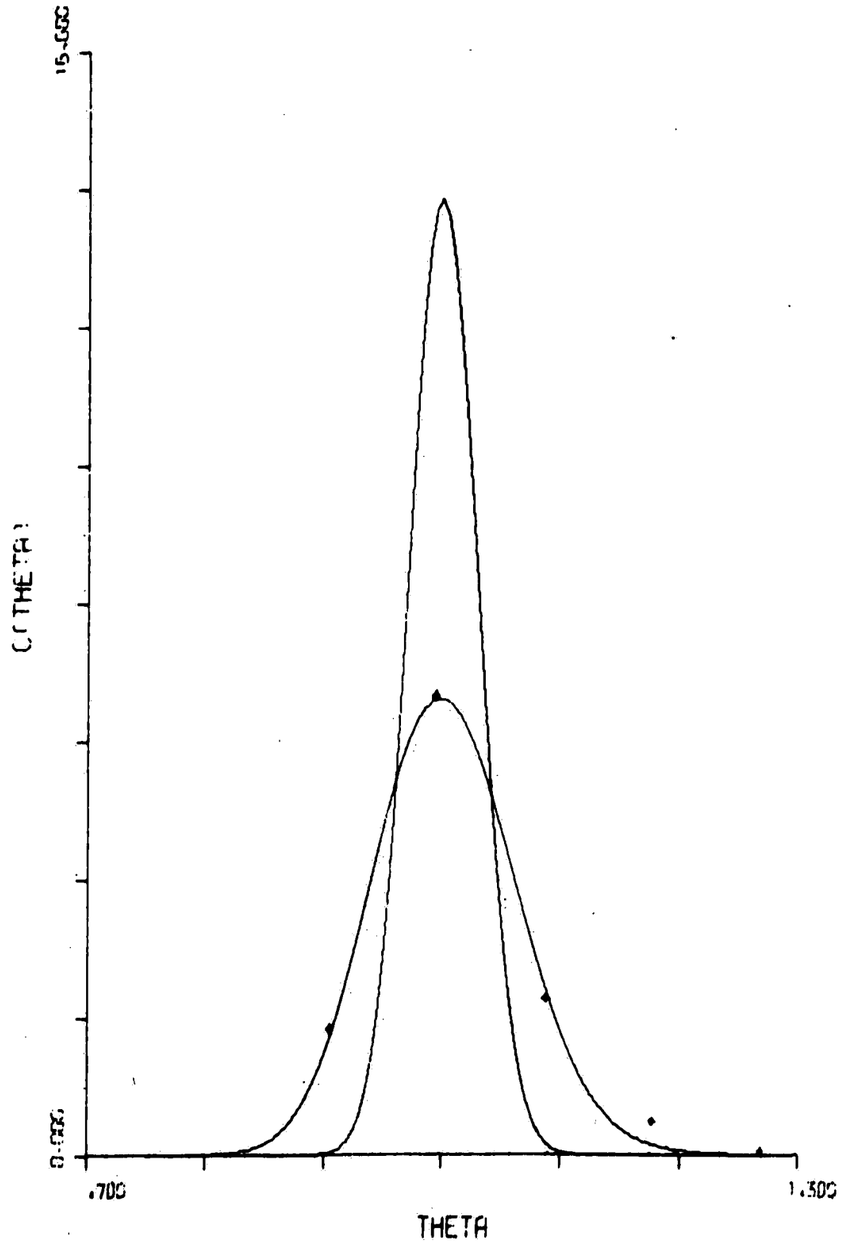
C(THETA) VS. THETA (8/9/78)

Graph No. 11



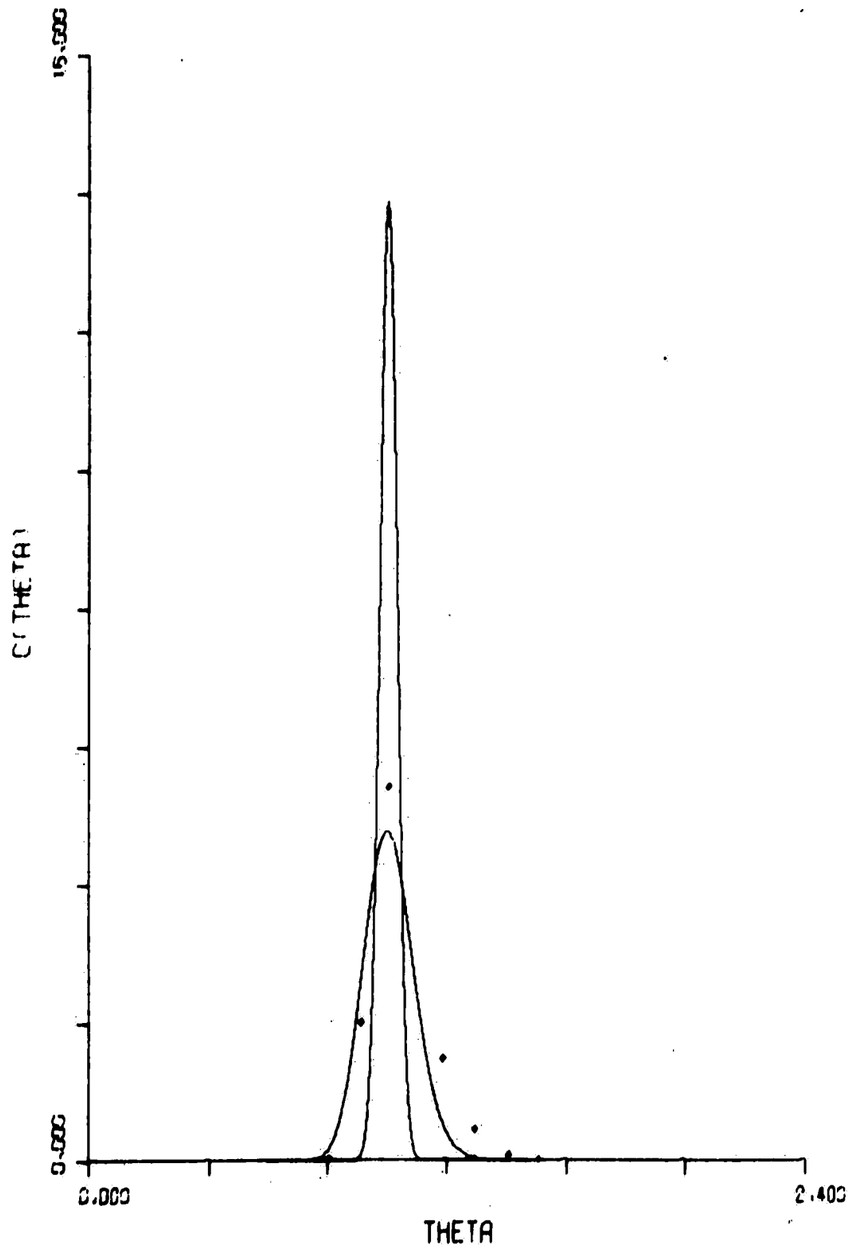
C(THETA) VS. THETA (8/16/78)

Graph No. 12



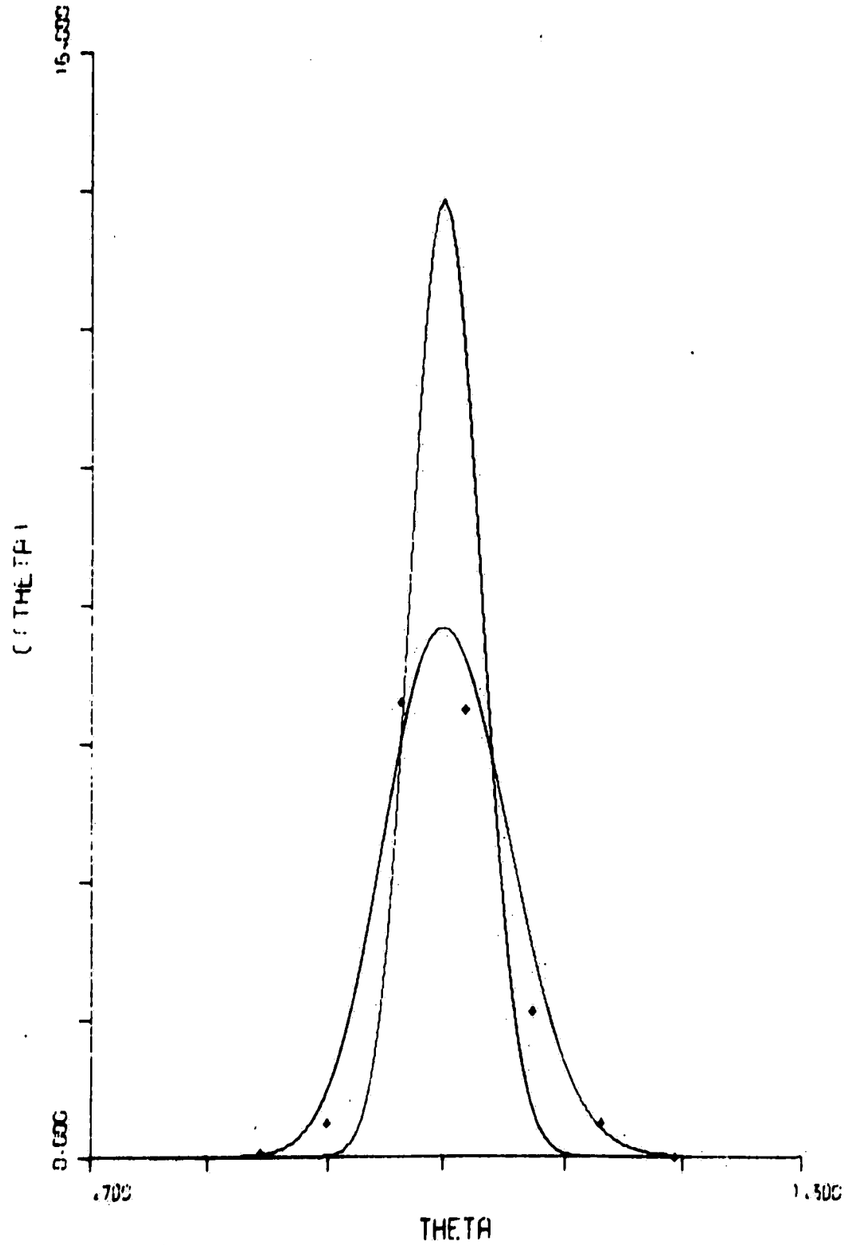
C(THETA) VS. THETA (8/18/78)

Graph No. 13



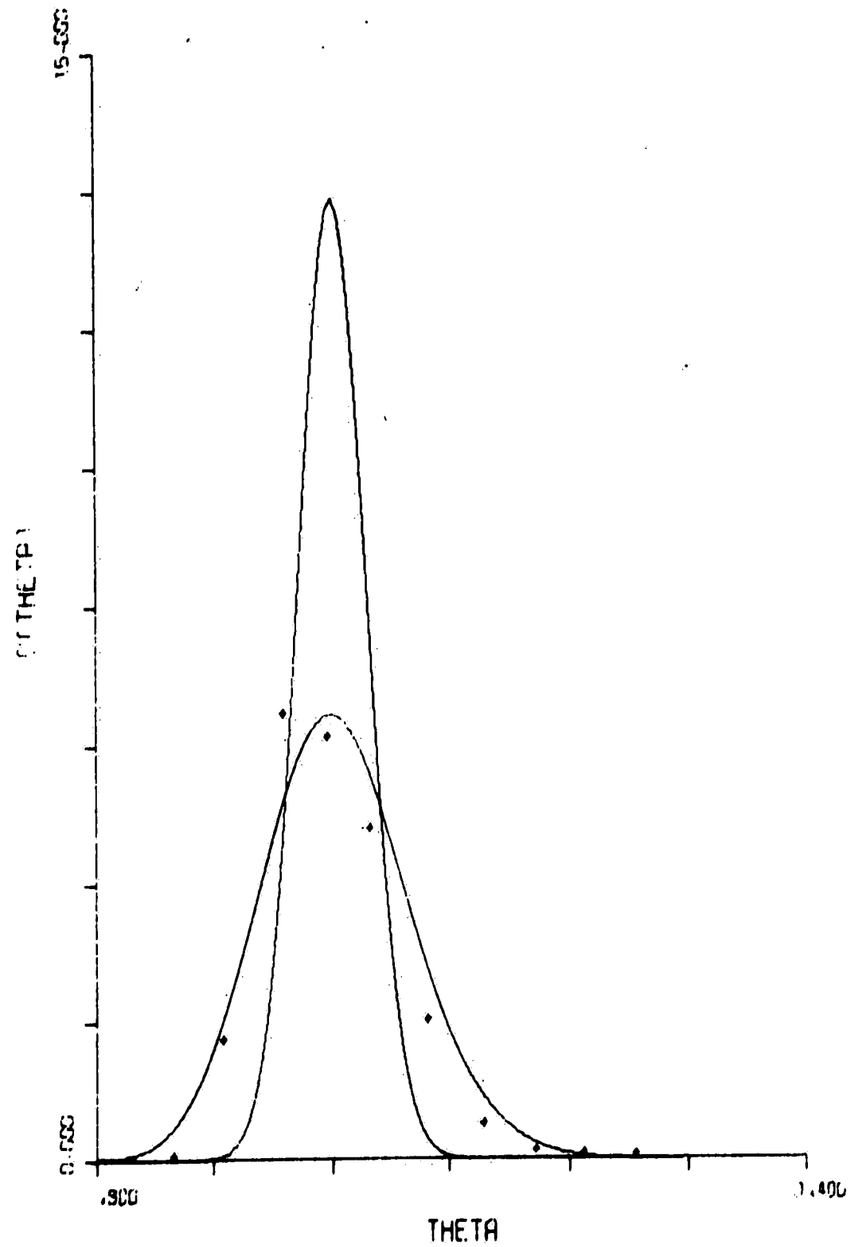
C(THETA) VS. THETA (8/22/78)

Graph No. 14



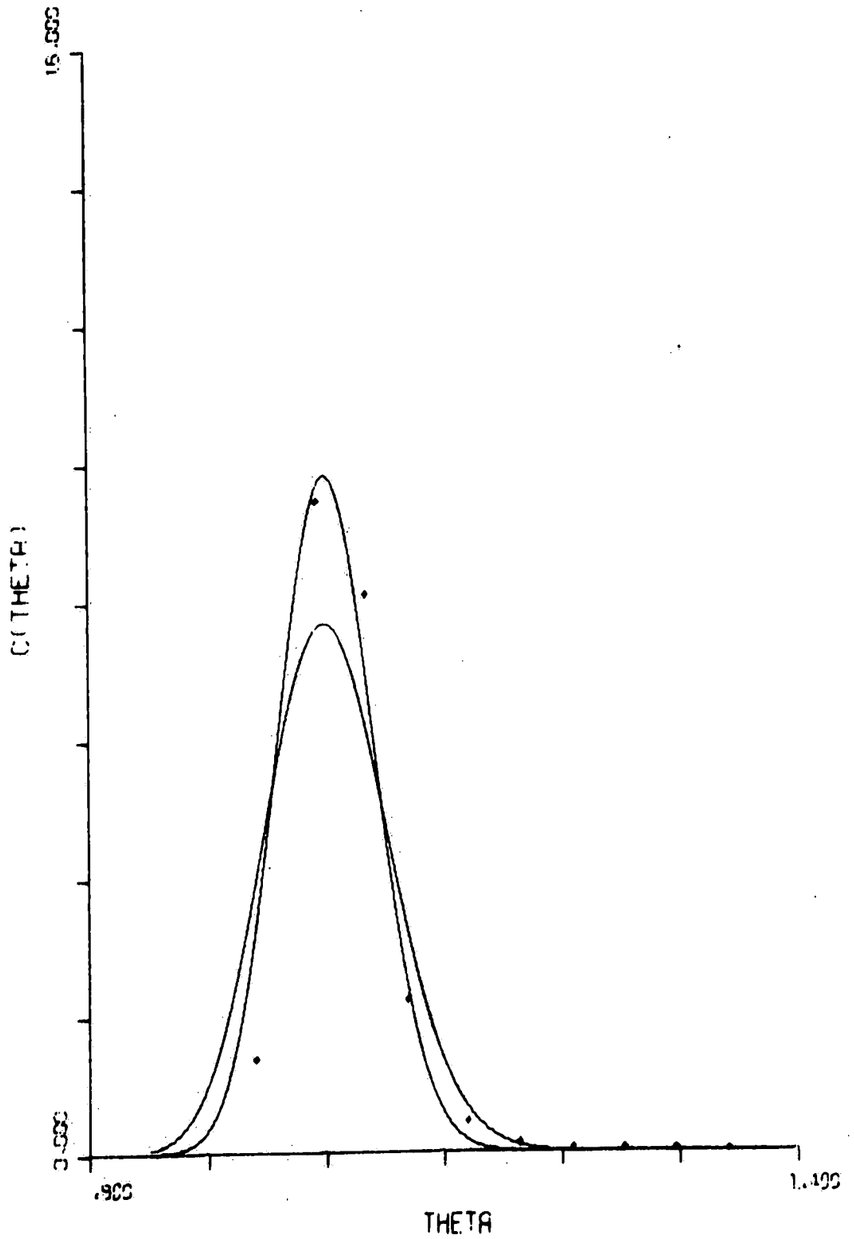
C(THETA) VS. THETA (8/22/78)

Graph No. 15



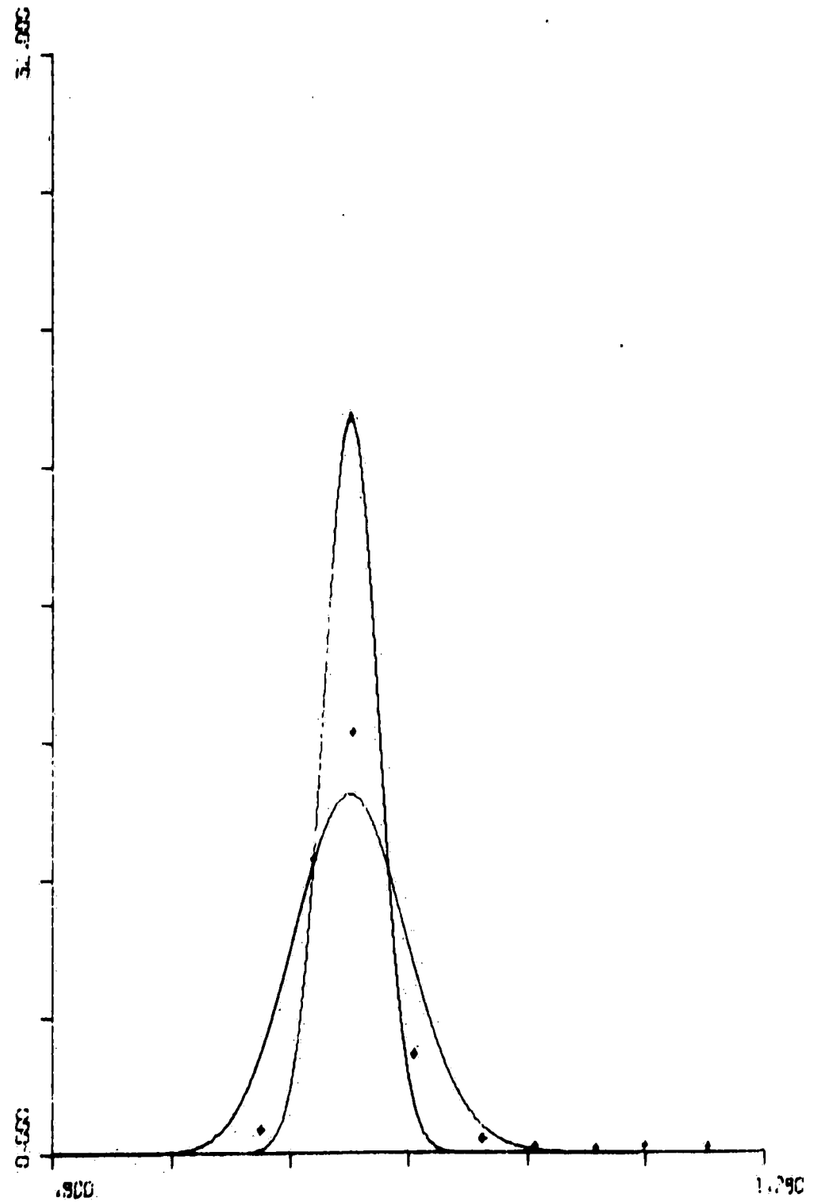
C(THETA) VS. THETA (8/24/78)

Graph No. 16



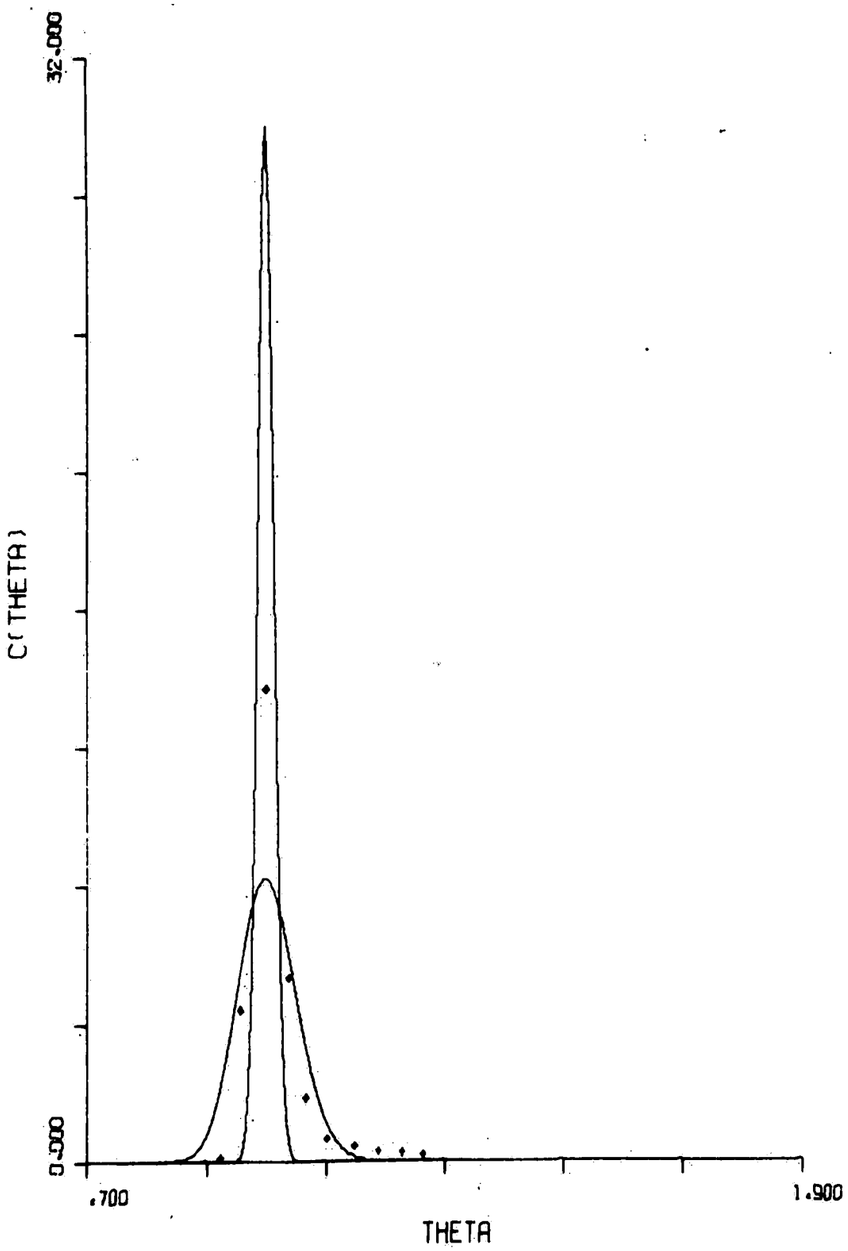
C(THETA) VS. THETA (11/10/78)

Graph No. 17



C(THETA) VS. THETA (2/6/79)

Graph No. 18



C(THETA) VS. THETA (2/9/79)

Table III—Comparison of Experimental and Predicted Dispersion Number

Date	D/uL(experimental) x 10^3	D/ud_t	d_t/L	D/uL(predicted) x 10^3
8/9/78	4.04	0.21	0.00617	1.30
8/16	0.59	0.21	0.00193	0.41
8/18	1.80	0.21	0.00193	0.41
8/22 (1)	3.48	0.21	0.00193	0.41
8/22 (2)	1.34	0.21	0.00193	0.41
8/24	1.91	0.21	0.00193	0.41
11/10	1.34	0.21	0.00391	0.82
2/6/79	0.72	0.21	0.00079	0.17
2/9	1.18	0.21	0.00042	0.088

Conclusions

The tracer technique developed provides an accurate way to determine the amount of sludge in United States Steel Corporation's coke-oven gas lines. For selected sections of the pipelines, sludge volumes measured by the tracer technique agreed well with sludge volume estimates made by mechanically probing the lines. Because of the inert character of the sulfur hexafluoride tracer and its detectability in low concentrations, and because of the simplicity of the technique, the method should be adaptable to other large diameter gas pipelines. However, accuracy is required to determine the precise quantity of tracer injected because of the sensitivity of the sludge calculations to deviations in this quantity.

The dispersion number may be calculated from the experimental data and compared with predicted values. The model chosen to describe the coke-oven gas lines was the doubly-infinite axial-dispersed plug flow model, and the experimental data fit the model well.

Experimental values of the dispersion number are greater than predicted values. The predicted values are for straight, smooth, clean pipe. Because the experimental runs were done on an industrial line which follows the

ground on which it was built, the line has many bends and curves. Taylor(12) states that even a small amount of curvature has a significant effect on the dispersion number. Additionally, the sludge deposits may enhance mixing due to eddy formation and backmixing. These phenomena cause non-uniform mixing, resulting in an average dispersion coefficient. Also, the roughness of the gas lines is probably greater than commercial pipe. This suggests that the theoretical values which were determined for commercial pipe are low. The factors of curvature of the lines, bends, sludge deposits enhancing mixing, and increased roughness all partially account for the higher experimental dispersion numbers. No previous data on gas systems as large as the coke-oven gas lines was found in the literature. Therefore, further studies on such systems should be carried out in order to provide more data on these systems.

Nomenclature

A_{clean} = mean free cross-section of empty pipe, m^2

A_{free} = mean free cross-section available for flow, m^2

$c = c(t)$ = concentration of tracer, kg/m^3

C_θ = dimensionless concentration = $\dfrac{\bar{t}\ c}{\int_0^\infty c\,dt}$

d_t = pipe diameter, m

D = dispersion coefficient, m^2/sec

$E(t)$ = exit age distribution function

L = test length, m

Q = quantity tracer injected, kg

t = time, sec

$\bar{t}$ = peak time, sec

u = linear velocity, m/sec

$\bar{u}$ = mean linear velocity, m/sec

V = gas volumetric flow rate, m^3/sec

x = distance along test length, m

z = dimensionless distance = $\dfrac{x}{L}$

ε = roughness factor, m

σ^2 = variance of concentration-time curve, sec^2

σ_θ^2 = variance of C_θ curve, dimensionless

θ = dimensionless time = tu/L

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Appendix A—Equipment Details

Sulfur hexafluoride: commercial purity, 99.8 percent minimum purity, Matheson Company

Dichlorodifluoromethane: 99.0% minimum purity (liq. phase), Matheson Company

Packing glands: fitted with 2-inch to 1/2-inch reducer

Probes: 1/2-inch tubing or pipe drilled with 3/8-inch holes along length

Valves: manifold - 1/4 inch Whitey® ball valves with Swagelok® fittings
feed tanks - 1/2 inch quick-action valve

Pressure gauges: SF_6 tank - 0 to 30 psig, division by tenths
Freon-12 tank - 0 to 200 psig

Other equipment: walkie-talkies, stopwatches

Appendix B—Consistency Check for Gas-Sampling Bag Weight Method for Determining Quantity of Tracer Injected

1.0 psi tank pressure drop

	Bag 1	Bag 2	Bag 3	Bag 4
bag + SF_6	51.6 g	52.25 g	51.9 g	51.4 g
- bag	40.1 g	40.6 g	40.2 g	40.6 g
SF_6	11.5 g	11.65 g	11.7 g	10.8 g

Appendix C—Recommended Sampling Time Intervals as a Function of Test Length

Recommended Time Between Samples, sec	Test Length Range, ft
2	0 to 500
3	500 to 2500
5 to 10	2500 to 5000
10	5000 to 7500
10 to 15	7500 to 10,000

Appendix D—Gas Sample Analysis Reports

RL 00020 REV 11-72 10 001 0012

UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7803-0338-A1 -B1 Series

PROJECT NO. 15-D-506-134

REQUEST DATE 8/9/78

REPORT DATE 8/29/78

REPORT OF ANALYSIS - SPECIAL

FOR T. J. Fediw MS NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7803-0338-A1 -B1 - Gas sampling bags containing coke-oven gas.

ANALYTICAL WORK REQUESTED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7803-0338 (series A1 thru A13 and B1 thru B13) was analyzed by means of a GC technique for SF_6. (SF_6 was identified on the basis of retention time.)

Sample No.	SF_6, lbs/cu ft	Sample No.	SF_6, lbs/cu ft
7803-0338-A1	27×10^{-9}	7803-0338-B1	$<10 \times 10^{-9}$
-A2	98×10^{-9}	-B2	$<10 \times 10^{-9}$
-A3	102×10^{-9}	-B3	33×10^{-9}
-A4	22×10^{-9}	-B4	1937×10^{-9}
-A5	41×10^{-9}	-B5	5497×10^{-9}
-A6	2655×10^{-9}	-B6	5549×10^{-9}
-A7	1089×10^{-9}	-B7	1440×10^{-9}
-A8	304×10^{-9}	-B8	609×10^{-9}
-A9	81×10^{-9}	-B9	258×10^{-9}
-A10	33×10^{-9}	-B10	124×10^{-9}
-A11	22×10^{-9}	-B11	100×10^{-9}
-A12	$<10 \times 10^{-9}$	-B12	83×10^{-9}
-A13	1089×10^{-9}*	-B13	39×10^{-9}

* Attributed to contaminated sample bag.

Note: 0.95 ppm SF_6/N_2 V/V is equivalent to 391×10^{-9} lbs/cu ft.

BOOK AND PAGE NO. 10189-5

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UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7803-0348-A1 -B1 Series
PROJECT NO. 15-D-506-134
REQUEST DATE 8/17/78
REPORT DATE 8/29/78

REPORT OF ANALYSIS - SPECIAL

FOR T. J. Fediw M S NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7803-0348-A1 -B1 - Gas sampling bags containing down-river gas from Clairton down-river gas lines.

ANALYTICAL WORK REQUESTED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7803-0348 (series A1 thru A13 and B1 thru B13) was analyzed by means of a GC technique. Identification of SF_6 was based on retention time.

Sample No.	SF_6, lbs/cu ft	Sample No.	SF_6, lbs/cu ft
7803-0348-A1	--	7803-0348-B1	--
-A2	--	-B2	--
-A3	--	-B3	--
-A4	--	-B4	134×10^{-9}
-A5	57×10^{-9}	-B5	535×10^{-9}
-A6	908×10^{-9}	-B6	1779×10^{-9}
-A7	3903×10^{-9}	-B7	3200×10^{-9}
-A8	7868×10^{-9}	-B8	4306×10^{-9}
-A9	11680×10^{-9}	-B9	4905×10^{-9}
-A10	7958×10^{-9}	-B10	3350×10^{-9}
-A11	5114×10^{-9}	-B11	1764×10^{-9}
-A12	3571×10^{-9}	-B12	359×10^{-9}
-A13	2201×10^{-9}	-B13	101×10^{-9}

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AL 20020 REV 11-72 10 001 0012

UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7803-0364-A_1 -B_1 Series

PROJECT NO. 15-D-506-134

REQUEST DATE 8/23/78

REPORT DATE 9/8/78

REPORT OF ANALYSIS - SPECIAL

FOR T. J. Fediw MS NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7803-0364-A -B Series - Gas sampling bags containing downriver gas.

ANALYTICAL WORK REQUESTED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7803-0364 (Series A_1 and B_1) was analyzed by means of a GC technique.

Sample No.	SF_6, lbs/cu ft	Sample No.	SF_6, lbs/cu ft
7803-0364-A1	--	7803-0364-B1	--
-A2	--	-B2	39×10^{-9}
-A3	29×10^{-9}	-B3	340×10^{-9}
-A4	1892×10^{-9}	-B4	3693×10^{-9}
-A5	5092×10^{-9}	-B5	3568×10^{-9}
-A6	1320×10^{-9}	-B6	1158×10^{-9}
-A7	375×10^{-9}	-B7	344×10^{-9}
-A8	121×10^{-9}	-B8	--
-A9	29×10^{-9}		

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RL 80020 REV 11-72 10 00 0012

UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7803-0371-B Series

PROJECT NO. 15-D-506-134

REQUEST DATE 8/24/78

REPORT DATE 9/8/78

REPORT OF ANALYSIS . SPECIAL

FOR T. J. Fediw M S NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7803-0371-B Series - Gas sampling bags containing downriver gas.

ANALYTICAL WORK REQUESTED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7803-0371 (Series B1 through B13) was analyzed by means of a GC technique.

Sample No.	SF_6, lbs/cu ft
7803-0371-B1	--
-B2	--
-B3	--
-B4	112×10^{-9}
-B5	1781×10^{-9}
-B6	6475×10^{-9}
-B7	5977×10^{-9}
-B8	4806×10^{-9}
-B9	1980×10^{-9}
-B10	629×10^{-9}
-B11	249×10^{-9}
-B12	131×10^{-9}
-B13	125×10^{-9}

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RL 20063 REV 11-77 20 03 0012

UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7803-0504 (See below)

PROJECT NO. 15-D-506-134

REQUEST DATE 11/13/78

REPORT DATE 11/22/78

REPORT OF ANALYSIS - SPECIAL

FOR T. J. Fediw MS NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7803-0504 (See below) - Gas sampling bags containing down-river gas.

ANALYTICAL WORK REQUESTED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7803-0504 (A1 thru A13 plus B1 thru B13) was analyzed for SF_6 by means of a GC technique.

Sample No.	SF_6 lbs/cu ft	Sample No.	SF_6 lbs/cu ft
7803-0504-A1	--	7803-0504-B1	--
-A2	--	-B2	--
-A3	--	-B3	--
-A4	442×10^{-9}	-B4	490×10^{-9}
-A5	3654×10^{-9}	-B5	3367×10^{-9}
-A6	5846×10^{-9}	-B6	2871×10^{-9}
-A7	2610×10^{-9}	-B7	783×10^{-9}
-A8	646×10^{-9}	-B8	166×10^{-9}
-A9	218×10^{-9}	-B9	65×10^{-9}
-A10	78×10^{-9}	-B10	57×10^{-9}
-A11	65×10^{-9}	-B11	38×10^{-9}
-A12	46×10^{-9}	-B12	33×10^{-9}
-A13	55×10^{-9}	-B13	30×10^{-9}

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PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7903-0056 (See below)

PROJECT NO. 15-B-510-134

REQUEST DATE 2/6/79

REPORT DATE 3/1/79

REPORT OF ANALYSIS - SPECIAL

FOR T. J. Fediw M S NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7903-0056-A and -B series - Gas sampling bags containing down-river gas.

ANALYTICAL WORK REQUESTED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7903-0056-A and -B series was analyzed by means of a GC technique.

Sample No.	SF_6, lbs/cu ft	Sample No.	SF_6, lbs/cu ft
7903-0056-A1	868×10^{-9}	7903-0056-B1	zero
-A2	leaked	-B2	229×10^{-9}
-A3	74×10^{-9}	-B3	2782×10^{-9}
-A4	41×10^{-9}	-B4	3898×10^{-9}
-A5	33×10^{-9}	-B5	943×10^{-9}
-A7	25×10^{-9}	-B6	198×10^{-9}
		-B7	70×10^{-9}
		-B8	27×10^{-9}
		-B9	33×10^{-9}
		-B10	27×10^{-9}

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PHYSICS AND ANALYTICAL DIVISION

RL SAMPLE NO. 7903-0066 (See below)

PROJECT NO. 15-B-510-134

REQUEST DATE 2/9/79

REPORT DATE 3/1/79

REPORT OF ANALYSIS - SPECIAL

FOR T. J. Fediw M S NO 57 DIVISION 3

SAMPLE MATERIAL AND DESCRIPTION

RL Sample No. 7903-0066-A and -B series - Gas sampling bags containing down-river gas.

ANALYTICAL WORK REQUIRED

Please determine concentration sulfur hexafluoride in each sample.

ANALYTICAL RESULTS

RL Sample No. 7903-0066-A and -B series was analyzed by means of a GC technique.

Sample No.	SF_6, lbs/cu ft	Sample No.	SF_6, lbs/cu ft
7903-0066-A1	8×10^{-9}	7903-0066-B1	10×10^{-9}
-A2	860×10^{-9}	-B2	8×10^{-9}
-A3	1692×10^{-9}	-B3	14×10^{-9}
-A4	No sample	-B4	38×10^{-9}
-A5	1926×10^{-9}	-B5	2763×10^{-9}
-A6	724×10^{-9}	-B6	8619×10^{-9}
-A7	No sample	-B7	3412×10^{-9}
-A8	210×10^{-9}	-B8	1099×10^{-9}
-A9	142×10^{-9}	-B9	469×10^{-9}
-A10	99×10^{-9}	-B10	295×10^{-9}
-A11	67×10^{-9}	-B11	215×10^{-9}
-A12	51×10^{-9}	-B12	115×10^{-9}
-A13	40×10^{-9}	-B13	104×10^{-9}

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Appendix E—Sample Calculations

I. % Sludge Calculation

Manual Calculation: Data from 8/22/78, run (2) B-line

Area under c,t curve: (graphical integration, Graph 5)

$$\text{Area} = \int_0^\infty c\,dt = 4.33 \times 10^{-5} \text{ lb sec/ft}^3$$

Peak time: (read from curve)

$$\bar{t} = 50.4 \text{ sec}$$

Test length: (from Carnegie Natural Gas Co.)

$$L = 2310 \text{ ft}^*$$

Quantity tracer injected:

Weight sample bag + SF_6	51.6 g
- Weight sample bag empty	40.2 g
Quantity SF_6 injected	11.4 g

$$\text{Quantity} = (11.4 \text{ g})\left(\frac{1 \text{ lb}}{453.6 \text{ g}}\right) = 0.0251 \text{ lb } SF_6$$

$$A_{free} = \frac{Q/\int_0^\infty c\,dt}{L/t} = \frac{(0.0251 \text{ lb})/(4.33 \times 10^{-5} \text{ lb sec/ft}^3)}{(2310 \text{ ft})/(50.4 \text{ sec})}$$

$$= 12.6 \text{ ft}^2$$

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* Distance may be slightly in error (±10 ft) for this example, due to non-parallel location of taps on A- and B-lines.

$$A_{clean} = \pi\frac{D^2}{4} = \frac{\pi}{4}\,(4.5\ ft)^2 = 15.9\ ft^2$$

$$\%\ Sludge = \left(\frac{A_{clean} - A_{free}}{A_{clean}}\right) \times 100 = \left(\frac{15.9 - 12.6}{15.9}\right) \times 100$$

$$= 20.5\%$$

II. Dispersion number calculations [data 8/22/78, run (2)]

$$\sigma^2 = \frac{\Sigma t_i^2\, c_i}{\sum ci} - \bar{t}^2 = \frac{\Sigma t_i^2\, c_i}{\sum ci} - \left(\frac{\Sigma t_i\, c_i}{\sum ci}\right)^2$$

$$= \frac{37,627,549}{14,353} - \left(\frac{733,903}{14,353}\right)^2$$

$$= 7.06\ sec^2$$

$$\bar{t} = \frac{733,903}{14,353} = 51.13\ sec$$

Now, using Equations (6) and (7),

$$\sigma_\theta^{\,2} = \frac{\sigma^2}{\bar{t}^2} = \frac{7.06}{(51.13)^2} = 0.00270$$

$$\frac{D}{uL} = \frac{1}{8}\,[\sqrt{8(0.00270) + 1} - 1] = 0.00134$$

Vita

The author was born in Reading, Pennsylvania, on February 18, 1956, to Mr. and Mrs. Theodore Fediw. He attended Lehigh University, where he received a Bachelor of Science degree in Chemical Engineering on January 6, 1978. During his studies at Lehigh, the author was a cooperative student with United States Steel Research Laboratory in Monroeville, Pennsylvania.